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INTERIOR BALLISTICS

by

M. E. Serevryakov

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672 Pages

(Part 9 of 10 Parts,
Pages 777-879)



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SECTION X - BALLISTIC DESIGN OF GUNS

General Remarks

The ballistic design of guns represents one of the most important departments concluding the theoretical course in applied interior ballistics, in which there is solved the principal problem of the latter, namely to determine the design data of the bore and the loading conditions at which a projectile of given caliber and weight, while being fired from a gun, acquires a definite predetermined initial velocity. In this connection, the maximum pressure of the gases evolved during the burning of the powder must not exceed a definite value p_m , which is usually stated in advance.

The design data of the bore comprise the following: the chamber volume W_0 ; the cross section s of the bore, including the rifling grooves; the length of the path of the projectile along the bore l_D ; the length of the chamber l_{KH} , with proper allowance for its enlargement λ relative to the section of the barrel; the number of volumes of expansion of the gases $\Lambda_D = \frac{l_D}{l_0} = \frac{W_D}{W_0}$ or the relative path of the projectile through the bore; the length of the bore L_{KH} ; the length of the barrel together with the breechblock L_{CT} ; and the volume of the bore $W_{KH} = W_0 + s l_D = s(l_0 + l_D)$.

The loading conditions comprise the following: the relative weight of the charge ω/q at a predetermined definite nature of the powder ($f, \alpha, \delta, \theta$); the loading density Δ ; the shape and principal dimensions of the powder grains (type of powder); and $l_K = e_1/u_1$.

For the variant selected in the design, there is conducted a computation of the variation of the pressure of the powder gases

and of the increase in the velocity of the projectile during the shot as functions of the path and of time. These data, plotted on diagrams in the form of $p-l$ and $v-l$ curves, as well as in the form of $p-t$ and $v-t$ curves, constitute the basic material for further computations by designers of the artillery system and ammunition.

The ballistic design of a gun provides the basic starting data for designing the extremely complex assembly represented by the modern artillery system together with the assortment of ammunition pertaining thereto.

On the basis of the data obtained in the ballistic design, the designer of the artillery system computes the barrel of the gun, the thickness of its walls, the fretting of the layers, the breechblock and the rifling grooves; these data also aid him in developing the design of the gun mount and of the recoil mechanism, which accumulates the energy of the recoil and returns the barrel of the gun to its original position after the shot.

Using the same ballistic-design data, the designer of the ammunition computes the body of the projectile and the rotating band, determines the stress in the explosive within the projectile, and computes the cartridge body and the percussion-cap mechanism, as well as the mechanisms of the firing devices and time fuzes.

On the basis of the shape and dimensions of the powder established in the design, the powder engineer computes the dies through which it is necessary to compact the powder mass of a given nature and determines the technological process required to produce the necessary dimensions and shape of the powder when the latter is finished in its final form.

Consequently, the design of the principal assemblies of an

artillery system and of the ammunition pertaining thereto depends in considerable measure upon how rationally the ballistic design of the bore has been developed. The rational design of the bore, however, depends upon the thoroughness of the study and knowledge of the general relations which connect the elements of the shot (gas pressure, velocity and path of the projectile) and its characteristic features with the design data of the barrel and the loading conditions.

In contrast with the "direct" problem of interior ballistics (computation of the gas-pressure and projectile-velocity curves), which yields only one single solution for a predetermined barrel design and given loading conditions, the problem of ballistic design, even for a predetermined pressure p_m , admits of a multiplicity of solutions for the barrel design and for the loading conditions, which assure attainment of the predetermined initial velocity by a projectile of given weight and caliber.

In connection with such an indeterminately large number of variants of the solution of the problem, there arises the question of introducing a definite procedure for the computation of variants satisfying a given assignment and selecting a criterion for their evaluation.

A rational computing procedure must yield a solution of the problem within the shortest possible time and with a minimum number of variants.

For the theoretical justification of such a procedure, use must be made of the general relations of interior ballistics, which interconnect the design data of the bore, and of the loading conditions at definite values of the maximum gas pressure p_m and of the initial velocity of the projectile.

Once these relations have been established, it becomes possible

to outline the course of computation of the variants and to select for their evaluation one or another ballistic criterion, which characterizes the gun from the point of view of the rational nature of the solution.

But the ballistic criteria alone are not sufficient; it is necessary to take into account additional criteria, which are given in the tactical and technical requirements imposed upon the given gun when the assignment for the development of the design is issued.

On the basis of an analysis and a tactical evaluation of one or another tactical employment of artillery (destruction of live targets, attack upon tanks or aircraft, demolition of fortifications and obstacles, attack upon staffs and concentrations of enemy troops at great distances, etc.), there is issued an assignment to develop one or another system, for example an antiaircraft gun with a definite height of destruction of the target, or a heavy howitzer for the demolition of concrete fortifications, or else an antitank gun capable of piercing armor of definite thickness at a predetermined distance.

Knowing the action of the projectile at the target, and taking account of the ratio of the weight of the explosive to the weight of the projectile as a whole, the weight and caliber of the projectile are designated ($\omega_{BB}/q = 0.10-0.20$ for demolition shells, $0.02-0.05$ for armor-piercing projectiles). Thereupon, using the formulas and tables of interior ballistics, there is computed the initial velocity of the projectile required in order that a projectile possessing definite caliber, weight, and shape give the necessary range, or else, for a predetermined range, have the impact velocity needed

to pierce armor of predetermined thickness^{*)}.

In this connection, there are sometimes imposed additional requirements, for example that the gun have as small a weight as possible, or even a weight predetermined in advance, both in the traveling position and in the firing position, or else that the length of the gun be less than so many calibers, or else that an already existing shell case or gun mount be utilized.

The totality of all the above-mentioned requirements constitutes the so-called tactical and technical specifications imposed upon the gun being designed during the issuance of the assignment.

The additional conditions included in the tactical and technical specifications exert an influence upon the choice of the ballistic solution and sometimes makes it necessary to arrive at a design that is not completely rational from the ballistic point of view. For example, the 1927 model 76 mm regiment artillery gun has an excessively large chamber volume, combined with too small a number of expansion volumes and a cartridge of large weight and over-all dimensions. The 1909 model 76 mm mountain gun gives the same velocity of the projectile at the same gas pressure with a considerably smaller chamber volume, weight of the charge, and weight of the entire cartridge, and with the same bore volume. There is no doubt that the last-mentioned gun is much better designed from the ballistic point of view than the regiment artillery gun.

But the introduction of the regiment artillery gun of the above-mentioned design was dictated by considerations that were no longer

^{*)}To compute the velocity needed to pierce armor, use is made of the formula of Jacob and de Marre, $v_c = k / (d^{0.75} B^{0.7}) / (q^{0.5} \cos \alpha)^{0.7}$, where k is the coefficient of strength of the armor ($k = 2200-2400$).

ballistic in character.

The art of the designer called upon to develop a ballistic design consists in considerable measure in arriving at a design that is rational from the point of view of interior ballistics while taking into account all the tactical and technical specifications.

A rational procedure for ballistic design must provide the shortest route to finding a solution satisfying all the requirements imposed by making a deliberate choice of each of the designated variants. In this connection, it is necessary to know in advance the direction and character of variation of the principal parameters and criteria which determine the expediency of the given variant; the computation must merely clarify the quantitative relations.

The principal relations which determine the connection between the design data of the bore of the gun and the loading conditions are obtained by solving the inverse problem for a predetermined caliber of the gun, weight of the projectile, and initial velocity of the projectile, and for a chosen maximum pressure.

The establishment of these general relations constitutes the subject matter of the chapter entitled "Theoretical Principles of Ballistic Design of Guns."

In establishing the general relations needed for ballistic design, it becomes necessary to resort to certain auxiliary functions and tables, which are obtained by additional treatment of the basic tables of Professor N.F. Drozdov, as well as of the ANII and GAU tables with "normal" values of the constants assumed therein.

These tables can also be utilized (and this is widely done in practice) for powders possessing a shape different from that of

strip-type powders, with a propellant force of the powder that is not equal to 950,000 kg·dm/kg, and even for combination charges consisting of two types of powder.

Since the method of Professor Drozdov is based on the usual assumptions accepted in solving the principal problem of pyrodynamics, the same assumptions are also accepted in their entirety in the theoretical solution associated with the ballistic design (geometric law of burning, law of rate of burning $u = u_p$, average gas pressure in the initial air space, etc.).

There are available at the present time many investigations relating to the theory of ballistic design. Mention should be made of the work of the following authors in our country.

From 1910 through 1948, Professor N.F. Drozdov has illuminated a series of questions connected with ballistic design and has initiated the fundamental direction for the work of the Russian school with respect to the gun of maximum power as a gun capable of ensuring the maximum velocity of the projectile $\left(\frac{mv_D^2}{2}\right)_{\max}$ in a gun of given length at a predetermined maximum pressure. The French school had defined the gun of maximum power as a gun with the maximum total work $\left(\frac{\varphi mv_D^2}{2}\right)_{\max}$. The tables of Professor N.F. Drozdov have received widespread acceptance and application in design offices.

Professor I.P. Grave, in his course of pyrodynamics (1934-1937), gave the most complete investigation of the fundamental relations, stated the theory of ballistic design as developed by various authors, and presented a series of his own studies in this field.

Professor V.E. Slukhotsky, who has devoted his attention to

problems of ballistic design since 1934, was the first to apply to ballistic design a consideration of the accuracy life of the barrel. Under his direction, there were compiled both the general 1942 GAU tables in three issues and the special issue of tables for ballistic computation (TBR), which are very convenient for practical use.

In 1939, Professor B.N. Okunev presented an analysis of the influence of certain parameters upon the "productivity" of an artillery system, compiled a number of tables, and outlined the general principles governing the choice of a ballistic solution.

In work performed in 1939-1946, Professor D.A. Ventsel presented the theory of ballistic design as applicable principally to small arms, in addition to which he also compiled special tables for various constants.

From 1940 through 1945, M.S. Gorokhov published a series of investigations supplemented by a large number of auxiliary tables and diagrams, which make it possible to establish general relations.

The author of the present book established in 1940 the concept of economic loading conditions, developed the theory of "the gun of minimum volume," which possesses considerably more advantageous characteristics than the earlier "gun of maximum power" advocated by the French school, and, on the basis of general relations, worked out a procedure of ballistic design with the use of a "directive diagram" for the choice of variants.

As a result of all these investigations by our scientists, the principles of ballistic design have in our country attained a high theoretical level and have been coordinated with tactical and technical requirements.

CHAPTER 1 - BASIC DATA

1. BALLISTIC CHARACTERISTICS OF GUNS.

— In connection with the indefinitely large number of possible solutions in ballistic design, there arises the question of the choice of criteria for the evaluation of design variants obtained by computation.

Every gun is characterized by a definite system of ballistic characteristics, which can be broken up into three groups.

- a) Design characteristics of the bore of the gun.
- b) Characteristics of the loading conditions.
- c) Energy characteristics of the shot.

Some of the characteristics, which have the most essential importance, may be selected as criteria for the evaluation of variants, in which connection it is also necessary to take into account the tactical and technical specifications imposed during the issuance of the assignment.

There is presented below an enumeration of the principal and most important ballistic characteristics of a gun.

A. Design Characteristics of Gun.

1. The chamber volume is characterized by its ratio to the weight of the projectile, W_0/q , which determines the magnitude of the initial velocity of the projectile. Depending upon the velocity v_D , the quantity W_0/q is varied within wide limits - from 0.1 to 2.0.

The chamber volume is sometimes characterized by the ratio W_0/d^3 , which also varies within wide limits (1.6-33.0 according to V.E. Slukhotsky).

2. The length of the barrel and length of the bore in terms of calibers, L_{CT}/d and L_{KH}/d . These quantities increase as the velocity

of the projectile and the coefficient of the weight of the projectile $c_q = q/d^3$ increase and may reach 150 and more calibers for $v_D = 1500$ m/sec.

3. The number of volumes of expansion of the gases in the bore $\Lambda_D = l_D/l_0 = W_D/W_0$, or the relative path of the projectile expressed in terms of nominal chamber lengths, is a most important design characteristic, which determines the type of gun. The larger the relative chamber volume the smaller is Λ_D . In modern guns, Λ_D varies in the range of 3.0-10.0; in guns of great power, $\Lambda_D = 3-4$; in automatic guns with small chambers, $\Lambda_D = 8-10$. Under otherwise identical conditions, a barrel of minimum weight is obtained with $\Lambda_D = 5-6$.

4. The characteristic of the depth of the rifling grooves n_s is determined from the formula $s = n_s d^2$, where n_s is about 0.80 at $t_n = 0.01d$ and $n_s = 0.83$ at $t_n = 0.02d$.

5. The coefficient of widening of the chamber $\chi = l_0/l_{KH} > 1$ (sometimes called the bottle-shape coefficient) influences the total length of the bore.

In artillery systems, χ varies from 1.05 to 3 (according to V.E.Slukhotsky); in small arms and antitank rifles, it reaches 4 and more.

B. Characteristics of Loading Conditions.

6. The loading density $\Delta = w/W_0$ varies within very wide limits, as follows:

In small arms	0.80-0.95
In powerful artillery systems	0.65-0.78
In ordinary guns	0.55-0.70
In howitzers with full charges	0.45-0.60

In howitzers with reduced charges. 0.10-0.35

In mortars 0.03-0.12

The loading density usually increases with increasing p_m and v_D .

7. The relative weight of the projectile ω/q , which is what principally determines the velocity of the projectile and the work of displacement of the gases of the charge itself, varies within very wide limits - from 0.01 to 1.5.

8. The coefficient of the weight of the projectile $c_q = q/d^3$ is one of the important characteristics determining the velocity of the projectile in a given gun.

For a predetermined velocity of the projectile, the quantities l_0/d , l_D/d , L_{KH}/d , and l_K/d are directly proportional to c_q ; the smaller c_q the smaller are the overall dimensions of the gun, and the finer is the powder required to maintain the predetermined p_{max} .

For armor-piercing shells of ordinary type

$$c_q = 16-18 \text{ kg/dm}^3$$

For demolition shells

$$c_q = 12-16 \text{ kg/dm}^3$$

For subcaliber armor-piercing projectiles with cores

$$c_q = 6-10 \text{ kg/dm}^3$$

For coil projectiles with special armor-piercing cores

$$c_q = \text{about } 6-7 \text{ kg/dm}^3$$

For light bullets

$$c_q = \text{about } 20-22 \text{ kg/dm}^3$$

For heavy and armor-piercing bullets with special cores

$$c_q = \text{about } 25-30 \text{ kg/dm}^3$$

9. The relative pressure impulse of the powder (expressed in calibers) l_K/d serves as a characteristic of the correspondence of the thickness of the powder to the caliber, as well as of the power of the gun.

For a velocity $v_D = 350-700$ m/sec, $I_K/d = 500-1000$.

If the length of the barrel is increased with the caliber unchanged, I_K/d increases; for example, in a rifle at $v_D = 870$ m/sec, $I_K/d =$ about 3000; in very powerful modern antitank rifles, I_K/d reaches the magnitude of 5000, where I_K is expressed in $\text{kg/dm}^2 \cdot \text{sec}$ and d in dm.

10. The loading parameter $B = s^2 I_K^2 g / f \omega \varphi q$ combines all three preceding parameters (ω/q , c_q , and I_K/d) and represents the principal characteristic determining the magnitude of the maximum pressure p_m and the position of the projectile at the end of burning of the powder Δ_K .

The smaller B the higher is p_m and the smaller is Δ_K ; and, on the contrary, as B increases, the magnitude of p_m decreases and Δ_K increases.

For normal loading conditions, independently of the magnitude of Δ and p_m , the average value of the quantity B is 1.9-2.0.

The parameter B is dimensionless, and for an analysis of the influence of the individual factors composing it, it is conveniently represented in the following form, which is based not on the absolute values, but on the relative values of the individual characteristics of the loading conditions:

$$B = \frac{n_s^2 d^4 I_K^2 g}{f \frac{\omega}{q} \varphi q^2} = \frac{g n_s^2 \left(\frac{I_K}{d} \right)^2}{f \frac{\omega}{q} \varphi \left(\frac{q}{d^3} \right)^2} = \frac{g n_s^2 \left(\frac{I_K}{d} \right)^2}{f \frac{\omega}{q} \varphi c_q^2},$$

where $\varphi = a + b \omega/q$ is a function of ω/q .

Consequently, the parameter B , with the propellant force of the powder constant, depends upon ω/q , $c_q = q/d^3$, and I_K/d , the ratio I_K/d being a means for changing the maximum pressure p_m and the position of the projectile at the end of burning of the powder without

considerably changing the velocity of the projectile; as for the quantities ω/q and c_q , they influence principally the initial velocity of the projectile, and their influence upon p_m may be compensated for by a corresponding change in l_K/d .

C. Energy Characteristics.

11. The coefficient of power $C_e = E_D/d^3 = c_q v_D^2/2g$ is the determining quantity for choosing in the design the initial elements p_m , χ , Δ , and W_0/d^3 (from the table of V.E. Slukhotsky or from the diagram of Schneider). As a rule, C_e varies in the range of 100-1700 tm/dm^3 .

12. The coefficient of utilization of unit charge weight:

$$\gamma_w = \frac{E_D}{\omega} = \frac{q v_D^2}{2g\omega} = \frac{v_D^2}{2g} : \frac{\omega}{q} \frac{\text{tm}}{\text{kg}}.$$

is as follows (in tm/kg).

For medium-power guns	$\gamma_w = 120-140$
For very high projectile speeds	$\gamma_w = 80-90$
For rifles and antitank rifles	$\gamma_w = 100-110$
For howitzers with full charges	$\gamma_w = 140-160$

13. The efficiency of the powder charge:

$$r_D = \frac{E_D \theta}{f\omega} = \gamma_w \frac{\theta}{f}$$

is proportional to the coefficient γ_w and varies in the range of 0.20-0.30.

14. The characteristic of the position of the projectile at the end of burning of the powder:

$$\gamma_K = \frac{l_K}{l_D} = \frac{\Lambda_K}{\Lambda_D}.$$

is as follows:

For guns

$$\gamma_K = 0.50-0.70$$

For howitzers with
full charges

$$\gamma_K = 0.25-0.30$$

15. The characteristic of utilization of the working volume of the chamber, or the characteristic of filling of the indicator diagram, is:

$$\gamma_D = \frac{p_{CH}}{p_m} = \frac{\varphi E_D}{W_D p_m} = \frac{\varphi q v_D^2}{2g W_D p_m}$$

where $W_D = s l_D = W_0 \Lambda_D$.

As Λ_D increases from 3 to 10, γ_D usually decreases from 0.70 to 0.40.

16. The characteristic of utilization of the total volume of the bore is:

$$R_D = \frac{\varphi E_D}{W_{KH} p_m} = \frac{\varphi q v_D^2}{2g W_{KH} p_m}$$

where:

$$W_{KH} = W_0(1 + \Lambda_D) = s(l_0 + l_D);$$

$$R_D = \gamma_D \frac{\Lambda_D}{\Lambda_D + 1}$$

17. The characteristic of the accuracy life of the barrel N. In our country, one of the most widespread formulas for taking into account the accuracy life of the bore of guns is the formula of Professor V.E. Slukhotsky, which includes in itself a series of ballistic characteristics of the gun.

In firing single shots, the expression for N has the following form:

$$N = k_1 k_2 k_3 \rho \frac{D_0^2 - d^2}{0.0022 p_0 \frac{d}{\epsilon} 10^{-3} + 0.002 t_1} \cdot \frac{\Lambda_D + 1}{\omega v_D^2 \sqrt{\Lambda_D} \left(\frac{v_1}{v_D} \right)^2 + \left(\frac{v_2}{v_D} \right)^2 - 7} \quad (118)$$

where k_1 is a coefficient depending upon the caliber of the gun;

k_2 is a coefficient varying with the rifling twist;

k_3 is a coefficient varying with the depth of rifling;

D_0 is the outer maximum diameter of the rotating band of the projectile;

ϵ is the thickness of the surface layer of the bore;

t_1 is the temperature of burning of the powder in $^{\circ}\text{C}$:

$$t_1^{\circ} = T_1^{\circ} - 273;$$

ρ is the resilience of the metal of the tube;

v_1 is the average gas velocity in the throat of the chamber during the motion of the projectile through the bore;

v_2 is the average gas velocity in the throat of the chamber during the period of the aftereffect of the gases;

p_0 is the initial pressure.

In computing the magnitude of N in accordance with Formula (118), the quantities d and D_0 must be taken in mm, p_0 in kg/cm^2 , v_D in m/sec.

The coefficient k_1 , expressed as a function of caliber, is given in the following tabulation:

$d, \text{ mm}$	50	100	150	200	250	300
$k_1 \cdot 10^{-6}$	15.80	7.10	3.40	2.00	1.96	1.93

Professor Slukhotsky recommends that the coefficients k_2 and k_3 be taken as:

$$k_2 = 1 \text{ and } k_3 = 1$$

The quantity $d \cdot 10^{-3}$ is taken, on the average, as 1.28 for artillery guns and as 1.40 for small arms.

The ratio v_2/v_D is usually small in comparison with $\Lambda_D(v_1/v_D)^2$ and may be neglected.

The ratio v_1/v_D is determined with the aid of a special table as a function of Λ_D and X_H , where $X_H = l_0/\lambda_H$ and $\lambda_H = l_{KM} + 0.75d$ is the distance from the bottom to the throat of the chamber:

$$X_H = \frac{1}{\frac{1}{X} + \frac{0.75d}{l_0}}$$

Table 15 - Table of Values of v_1/v_D .

$\Lambda_D \backslash X_H$	3	4	5	6	7	8	9	10
0.6	0.270	0.256	0.243	0.233	0.223	0.215	0.211	0.208
0.8	0.237	0.222	0.209	0.199	0.189	0.180	0.174	0.168
1.0	0.213	0.197	0.184	0.174	0.165	0.157	0.150	0.143
1.2	0.196	0.180	0.167	0.157	0.149	0.141	0.134	0.128
1.4	0.183	0.166	0.153	0.143	0.135	0.128	0.121	0.115
1.6	0.171	0.154	0.141	0.131	0.124	0.116	0.111	0.105
1.8	0.161	0.144	0.131	0.122	0.115	0.109	0.103	0.098
2.0	0.152	0.135	0.123	0.114	0.107	0.101	0.096	0.092
2.2	0.144	0.128	0.116	0.107	0.100	0.095	0.090	0.086
2.6	0.131	0.116	0.105	0.097	0.091	0.086	0.081	0.077
3.0	0.120	0.105	0.095	0.088	0.083	0.078	0.074	0.070

In accordance with Formula (118), it is possible to determine the actual number N of shots, which characterizes the accuracy life.

In a comparative evaluation of variants, it is possible to use

Professor Slukhotsky recommends that the coefficients k_2 and k_3 be taken as:

$$k_2 = 1 \text{ and } k_3 = 1$$

The quantity $d/\epsilon \cdot 10^{-3}$ is taken, on the average, as 1.28 for artillery guns and as 1.40 for small arms.

The ratio v_2/v_D is usually small in comparison with $\Lambda_D(v_1/v_D)^2$ and may be neglected.

The ratio v_1/v_D is determined with the aid of a special table as a function of Λ_D and χ_H , where $\chi_H = l_0/\lambda_H$ and $\lambda_H = l_{KH} + 0.75d$ is the distance from the bottom to the throat of the chamber:

$$\chi_H = \frac{1}{\frac{1}{x} + \frac{0.75d}{l_0}}$$

Table 15 - Table of Values of v_1/v_D .

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0.6	0.270	0.256	0.243	0.233	0.223	0.215	0.211	0.208
0.8	0.237	0.222	0.209	0.199	0.189	0.180	0.174	0.168
1.0	0.213	0.197	0.184	0.174	0.165	0.157	0.150	0.143
1.2	0.196	0.180	0.167	0.157	0.149	0.141	0.134	0.128
1.4	0.183	0.166	0.153	0.143	0.135	0.128	0.121	0.115
1.6	0.171	0.154	0.141	0.131	0.124	0.116	0.111	0.105
1.8	0.161	0.144	0.131	0.122	0.115	0.109	0.103	0.098
2.0	0.152	0.135	0.123	0.114	0.107	0.101	0.096	0.092
2.2	0.144	0.128	0.116	0.107	0.100	0.095	0.090	0.086
2.6	0.131	0.116	0.105	0.097	0.091	0.086	0.081	0.077
3.0	0.120	0.105	0.095	0.088	0.083	0.078	0.074	0.070

In accordance with Formula (118), it is possible to determine the actual number N of shots, which characterizes the accuracy life.

In a comparative evaluation of variants, it is possible to use

the following abbreviated conditional expression:

$$N_{ycn}^* = K \frac{\Lambda_D + 1}{\omega \Lambda_D \left(\frac{v_1}{v_D} \right)^2}$$

(ycn* = conditional)

The product $\Lambda_D (v_1/v_D)^2$ varies within narrow limits, for which reason N_{ycn} in most cases increases with increasing Λ_D and with diminishing weight of the charge ω .

2. COLLECTION AND TREATMENT OF PRELIMINARY DATA.

On the basis of the tactical and technical specifications imposed in the assignment for already chosen values of the caliber d , the weight of the projectile q , and the initial velocity v_D , it is necessary to collect preliminary data relating to the characteristics of guns approaching the gun being designed in type and in their loading and firing conditions.

For these "related," already existing artillery systems, it is necessary to find the following characteristics, which are in part available as such and must in part be determined by supplementary computations: d , W_0 , s , l_{KH} , l_D , L_{HP} , L_{KH}/d , L_{CT}/d , q , the type of projectile, $c_q = q/d^3$, the nature of the powder (f , α , δ , θ), its shape and dimensions, the weight of the charge ω , $I_K = e_1/u_1$, P_m , and v_D .

All these characteristics may be obtained in various handbooks, firing tables, service manuals, descriptions and drawings of charges and projectiles, and drawings of the chamber and barrel.

In firing tables and other sources, there is usually given not the length of path of the projectile along the bore, but the length of the rifled part L_{HP} , which is smaller than l_D . The difference

depends upon the arrangement of the base of the projectile, which is to be found precisely in the drawings of the projectiles. As an approximation, it may be considered that $l_D = L_{HP} + (0.5 - 1.0)d$, 0.5d relating to old flat-bottomed shells, and 1.0d relating to contemporary modernized projectiles.

On the basis of the data obtained, the following characteristics must be computed:

$$\Delta, \frac{\omega}{q}, \frac{I_K}{d}, \gamma_\omega = \frac{E_D}{\omega} = \frac{v_D^2}{2g} : \frac{\omega}{q}; C_\epsilon = \frac{E_D}{d^3} = c_q \frac{v_D^2}{2g},$$

$$\gamma_D = \frac{p_{av.}}{p_m} = \frac{\varphi m v_D^2}{2s l_D p_m} = \frac{\varphi \gamma_\omega \Delta}{\Lambda_D p_m};$$

$$r_D = \frac{E_D \theta}{f \omega} = \gamma_\omega \frac{\theta}{f}; r' = \varphi r_D; R_D = \frac{\varphi m v_D^2}{2s(l_0 + l_D)p_m} = \gamma_D \frac{\Lambda_D}{\Lambda_D + 1}.$$

After collecting all these data, they must be summarized and treated in such a manner as to utilize the data obtained by experimental means to coordinate the results of computation with experiment (determination in accordance with selected tables of coefficients) and to designate the basic data for use in the computations associated with the particular assignment in hand.

3. CHOICE OF BALLISTIC CRITERIA FOR EVALUATION OF VARIANTS.

Among the characteristics mentioned above, c_q and C_ϵ are known from the conditions of the assignment; the remaining characteristics are determined during the computation of the variants. The following characteristics are most essential:

$$\Lambda_D = \frac{W_D}{W_0} = \frac{l_D}{l_0}, \frac{L_{KH}}{d} \text{ or } \frac{W_{KH}}{q} = \frac{W_0}{q}(\Lambda_D + 1), \frac{\omega}{q}, \gamma_K = \frac{\Lambda_K}{\Lambda_D},$$

$$\gamma_D = \frac{p_{av}}{p_m}, \quad \gamma_\omega = \frac{E_D}{\omega} \text{ and } N_{yca} \text{ or } N.$$

In evaluating variants, it is usually attempted to select those with the largest possible γ_D , R_D , and γ_ω ; with γ_K in the range of 0.60-0.70, which corresponds to the economical utilization of the charge; with the smallest possible value of ω/q ; and with a large Λ_D , which increases N_{yca} .

But, as γ_D and R_D increase, the coefficient γ_ω decreases; and, in order to reconcile these oppositely varying characteristics, it becomes necessary to select some intermediate relative solution.

In connection with this, mention should be made of attempts to provide a criterion combining the influence of these two conflicting criteria.

For example, Professor B.N. Okunev (1939) proposed to use as a characteristic of advantage of a variant the following quantity:

$$H = \sqrt{r' \gamma_D},$$

where:

$$r' = \frac{\varphi q v_D^2 \theta}{2 g f \omega} \quad \frac{\varphi \theta}{f} \gamma_\omega.$$

This quantity, independently of the chosen pressure p_m , has a maximum at the ratio $v = v_D/v_{np} = 0.52$. For small arms, Professor Okunev recommends taking $v > 0.52$ (0.55-0.56), for guns of great power $v < 0.52$ (0.48-0.50).

Professor I.P. Grave, in developing the idea of Professor Okunev, gave the following expression:

$$H' = \sqrt[m+n]{r_D^m \gamma_D^n},$$

without, however, indicating a method and criterion for the choice of the exponents m and n . Professor M.E. Serebryakov, in developing this proposal, accepted as a measure of advantage the following quantity:

$$H'' = \sqrt[1+\gamma]{R_D r_D^\gamma},$$

in which connection he did give a procedure for computing the quantity γ and showed that, depending upon the type of system, the exponent γ varies from 0 to 1.5.

The exponent γ or the quantity H'' depend in some measure upon the type of guns and in a certain measure reflect the influence of the tactical and technical specifications.

Professor V.E. Slukhotsky, while investigating a series of systems which had given good results in service, accepted for evaluating individual variants of a ballistic solution the criterion Z , as defined by the following expression:

$$Z = \gamma_\omega \gamma_L^4 \sqrt{N_{ycn}}.$$

This criterion takes into account not only ballistic, but also design and economic requirements, such as are necessarily imposed upon the system being designed. The design factors include the length of the barrel; the economic factors include the accuracy life N_{ycn} and the utilization of the charge γ_ω .

As a characteristic of utilization of the length of the body of the gun, use is made of a quantity that is analogous to the

quantity R_D :

$$\eta_L = \frac{q v_D^2}{L_{CT}}$$

Professor Siukhotsky believes the most advantageous variant to be that in which the quantity Z is largest.

As is seen, the problem of establishing such combined criteria is in the stage of development and accumulation of experimental data.

In the selection of basic variants in ballistic design, use was made until quite recently (1940) of special diagrams or tables of relative gun characteristics. Among the most widely used diagrams, there was, for example, that shown in Fig. 133, which represents the result of treatment by Engineer N.A. Upornikov of the system of artillery equipment designed by the Schneider works.

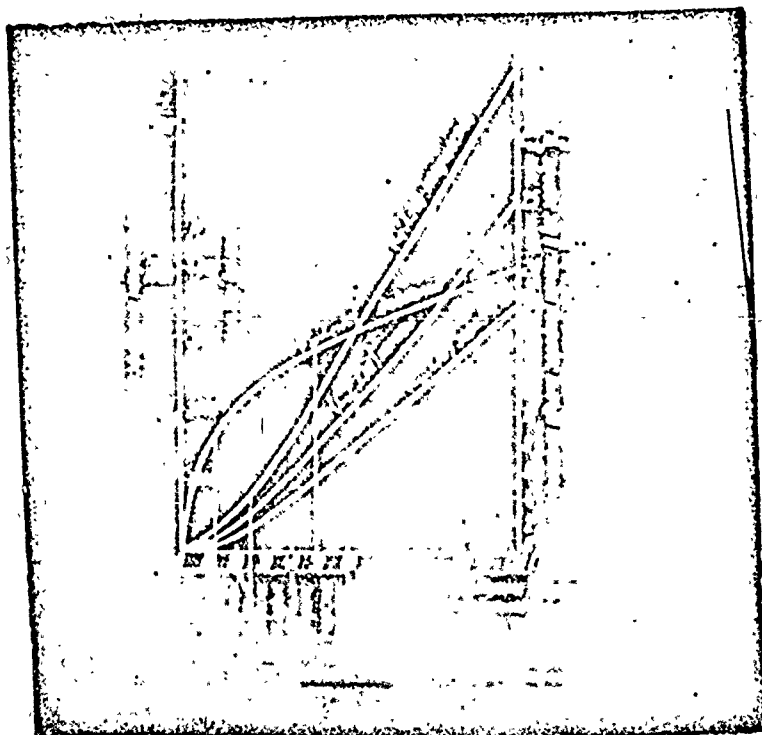


Fig. 157 -- Diagram of Basic Ballistic Characteristics.

- 1) Coefficient of power; 2) maximum pressure; 3) power;
- 4) pressure; 5) of chamber; 6) charge; 7) coefficient of volume of charge chamber and weight of charge;

GRAPHIC NOT REPRODUCIBLE

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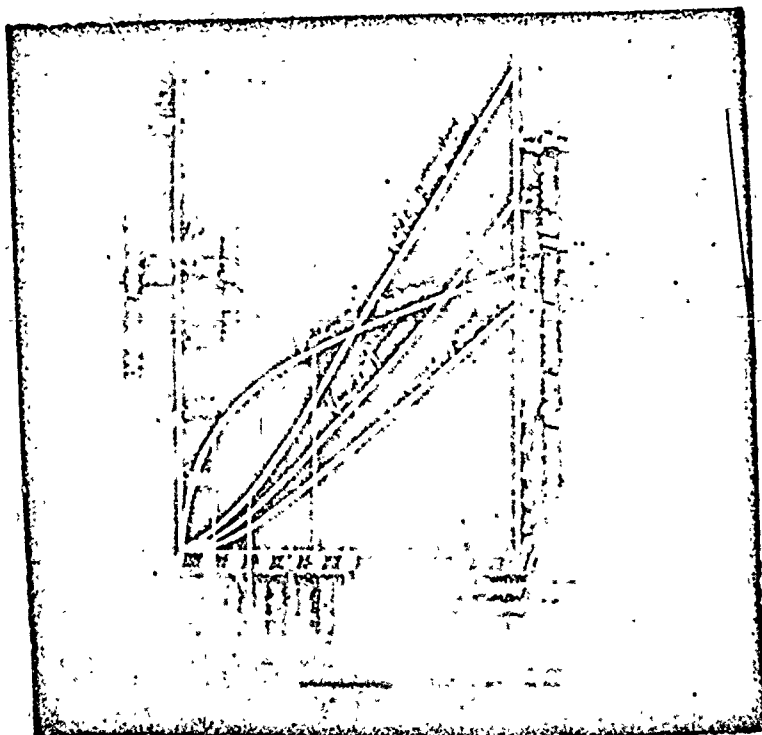


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- 1) Coefficient of power; 2) maximum pressure; 3) power;
- 4) pressure; 5) of chamber; 6) charge; 7) coefficient of volume of charge chamber and weight of charge;

GRAPHIC NOT REPRODUCIBLE

Fig. 157 (cont'd.)

8) mortars; 9) howitzers; 10) field guns; 11) naval guns; 12) super guns.

The basic quantity in the diagram is the coefficient of power $C_e = \frac{E_D}{d^3} \frac{t_m}{dm^3}$. In accordance with this quantity, there are found the total length of the barrel (expressed in calibers), L_{CT}/d , as well as the relative chamber volume $c_{w_0} = W_0/d^3$, the relative weight of the charge $c_w = w/d^3$, and the maximum pressure p_m . Knowing c_{w_0} and c_w , it is easy to find the loading density $\Delta = c_w/c_{w_0} = w/W_0$. To effect the transition from the relative chamber volume and the relative weight of the charge to the absolute values, it is necessary to multiply c_{w_0} and c_w by the cube of the caliber in decimeters. The coefficient of utilization of the charge can be found from the ratio $C_e/c_w = \gamma_w$.

An advantage of the diagram is the independence of its data from the caliber of the system.

As guiding material, use was also made of the table compiled in 1934 by V.E. Slukhotsky [20] on the basis of a treatment of data relating to the most successful among our own and foreign systems. At the present time, this table has been revised by its author on a more modern basis.

Both in the table of V.E. Slukhotsky and in the Schneider diagram, the basic quantity is the coefficient of power of the system; values for the quantities γ_w , p_m , Δ , χ , and L_{CT}/d are given as functions of the quantity $C_e = E_D/d^3$.

The table of V.E. Slukhotsky, as revised in accordance with the most recent data, is presented below:

CHAPTER 2 - THEORETICAL PRINCIPLES OF BALLISTIC DESIGN

1. MOST ADVANTAGEOUS AND MOST ECONOMICAL LOADING DENSITIES IN GUN AT GIVEN MAXIMUM PRESSURE. [21]

In a given gun with a definite volumetric expansion ratio $\Delta_D = l_D/l_0$, let the maximum gas pressure p_m be predetermined. It is necessary to follow the variation in the initial velocity of the projectile v_D required to maintain the pressure p_m constant during the simultaneous variation in the weight of the charge and in the thickness of the powder.

At the same time, it is also necessary to follow the variations in the coefficients of utilization of the unit weight of the charge $\eta_\omega = E_D/\omega$ and of utilization of the working space of the bore:

$$\eta_D = \frac{p_{av.}}{p_m} = \frac{\varphi m v_D^2}{2 s l_D p_m}$$

The minimum loading density at which a predetermined maximum pressure p_m is obtained in a given gun will be present in the case of instantaneous burning of the powder in the chamber space before the projectile begins moving.

In this case, we apply the following formula:

$$p_m = \frac{f \Delta_1}{l - \alpha \Delta_1},$$

from which:

$$\Delta_1 = \frac{p_m}{f + \alpha p_m} = \frac{1}{\frac{f}{p_m} + \alpha} \text{ and } \omega_1 = W_0 \Delta_1 = \frac{W_0}{\frac{f}{p_m} + \alpha}.$$

Now, in order to meet the condition $p_m = \text{const.}$, we shall increase the charge while simultaneously increasing the parameter

$B = s^2 I_K^2 / f \omega q_m$ in conformity with the following previously established relation:

$$B = \frac{a_m \Delta}{1 - \alpha \Delta},$$

where:

$$a_m = \frac{f F_2(\theta)}{p_m} \left(- \frac{0.32 f}{p_m} \text{ at } \theta = 0.2 \right).$$

In this case, the pressure impulse of the powder $I_K = e_1 / u_1$ will be expressed by the following formula:

$$I_K = \frac{\sqrt{K_m} \omega}{\sqrt{W_0 - \alpha \omega}},$$

where:

$$K_m = \frac{f^2 F_2(\theta) q_m}{p_m s^2} \quad \frac{a_m f q_m}{s^2}.$$

Note: The impulse increases with increasing ω ; consequently, the thickness of the charge e_1 increases.

In the presence of such a simultaneous variation in the weight of the charge (or loading density) and in the thickness of the powder, we shall obtain curves for the pressure as a function of the path of the projectile on which the pressure maximum, while remaining unchanged in magnitude, will, in conformity with the expression $l_m = l_0(1 - \alpha \Delta) [F_1(\theta) - 1]$, shift with increasing Δ toward the starting point of the motion, whereas the end of burning of the powder will shift toward the muzzle face. In this connection, we shall have a loading density Δ_1 at which the end of burning will occur precisely at the muzzle face.

As Δ and I_K grow further, there will be obtained incomplete

The v_D - Δ curve has its maximum at:

$$\Delta = \Delta_m;$$

$$v_{Di} = v_{Dm}.$$

and, consequently, there exists to the left from Δ_m a loading density $\Delta_E < \Delta_m < \Delta_i$ at which $v_{DE} = v_{Di}$.

Since the loading density Δ_E is considerably smaller than Δ_i (by 5-15%), we shall designate this loading density as the economical loading density.

At this loading density, the burning of the powder is completed sooner than at Δ_m or at Δ_i .

There is presented below a tabulation of some ballistic elements at various Δ for $\Delta_D = 6.0$ and $p_m = 2500 \text{ kg/cm}^2$.

Table 16

Δ	Δ_1	Δ_2	Δ_E	Δ_m	Δ_i
$\left\{ \begin{array}{l} \Delta \\ \eta_K = \frac{l_K}{l_D} \\ v_D \\ \eta_\omega = \frac{\epsilon_D}{\omega} \\ \eta_D = \frac{p_{av.}}{p_m} \end{array} \right.$	0.21	0.55	0.65	0.70	0.75
	0	0.30	0.55	0.72	1.00
	425	613	644	648	644
	178	130	121	114	105
	0.277	0.582	0.643	0.650	0.643

The results of computations carried out with the aid of the ANII tables have confirmed the above theoretical conclusion relating to the existence of Δ_m , Δ_E , and Δ_i .

In this connection, the coefficient of utilization of the unit

burning of the powder and a decrease in v_D .

Experiments and computations show that the initial velocity of the projectile v_D accompanying such an increase in Δ from Δ_1 to Δ_2 will first grow, then pass through a maximum at a certain $\Delta_m < \Delta_2$, and then slightly decrease; at $\Delta = \Delta_1$:

$$v_{D1} < v_{Dm}$$

Consequently, for a powder of a given shape and nature, there exists a $\Delta = \Delta_m$ at which, with the pressure p_m predetermined, the initial velocity of the projectile will have a maximum value. This loading density $\Delta = \Delta_m$ will be designated by us as the most advantageous loading density.

The difference between v_{D1} and v_{Dm} is generally small (0.5-2.0%), and, in the previous investigations conducted by the French school, it was assumed as an approximation that the maximum velocity is obtained when the burning of the powder is completed precisely at the muzzle face.

As a matter of actual fact, this is not so; the relation between v_D and Δ in a given gun at a predetermined p_m is apparent from the curve in Fig. 158.



Fig. 158 - Relation between v_D and Δ in
Given Gun at $p_m = \text{const.}$

GRAPHIC NOT REPRODUCIBLE

weight of the charge η_w is found to attain its maximum (178) for instantaneous burning, in spite of the low velocity of the projectile, and to decrease continuously to 105 at the maximum $\Delta = \Delta_1$.

The coefficient $\eta_D = p_{av.}/p_m$, on the other hand, increases rapidly at first, reaches its maximum at $\Delta = \Delta_m$, and thereupon slowly decreases. This decrease also continues to occur as Δ and the thickness of the powder further increase in the presence of incomplete burning of the powder.

The optimum utilization of the bore of the gun is obtained either at $\Delta = \Delta_m$ or, neglecting the small difference in velocities, at $\Delta = \Delta_E$, which gives a higher coefficient of utilization η_w (121 instead of 114 at $\Delta = \Delta_m$).

We thus obtain the following relations:

Δ	$\Delta_1 < \Delta_2 < \Delta_E < \Delta_m < \Delta_1$
v_D	$v_1 < v_2 < v_E < v_m > v_1 \quad (v = v_D)$
$\eta_K = \frac{l_K}{l_D}$	$0 < \eta_K < \eta_{KE} < \eta_{Km} < \eta_K = 1$
η_w	decreases
η_D	increases to $\Delta = \Delta_m$

$$v_E = v_1; \Delta_1 - \Delta_E = 0.07 \dots 0.10 = (10 - 15\%) \Delta_1$$

$$v_D = (1.005 - 1.02) v_1.$$

In practice, the economical loading density may be considered to be most advantageous.

These relations are generally applicable to various p_m and Δ , as well as to guns with various volumetric expansion ratios Λ_D .

The values of Δ_m , Δ_E , and Δ_1 are functions of the gun character-

istic Λ_D and of the magnitude of p_m at a given shape of the powder.

There are presented below tabulations of values of Δ_i , Δ_E , and B_E as functions of p_m and Λ_D ; these have been obtained by treatment of the ANII tables at the following powder characteristics: $\chi = 1.06$; $\chi\lambda = -0.06$; $\varphi = 1.05$; $f = 950,000 \text{ kg}\cdot\text{dm}/\text{kg}$; $\alpha = 0.98 \text{ dm}^3/\text{kg}$; $\delta = 1.6 \text{ kg}/\text{dm}^3$; $\theta = 0.20$; and for $p_0 = 300 \text{ kg}/\text{cm}^2$ (standard constants adopted by Professor Drozdov in his tables).

Tables 17 and 18 show that Δ_i and Δ_E increase as p_m and Λ_D increase. In conformity with theoretical conclusions, the increase in Δ_E is accompanied by an increase in the parameter B_E , as is apparent from Table 19.

Table 20 shows that the quantity $p_{av.}/p_m$ decreases with increasing Λ_D and with increasing p_m .

For economical Δ , $\eta_K = l_K/l_D$ at first decreases with increasing Λ_D , but then approaches a constant quantity.

Table 17 - Values of Δ_i (Burning of Powder at Muzzle Face). [207]

$\Lambda_D \backslash p_m$	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600
2	0.437	0.475	0.511	0.547	0.581	0.615	0.649	0.681	0.712	0.740
3	0.501	0.554	0.588	0.619	0.655	0.689	0.721	0.751	0.777	0.802
4	0.541	0.588	0.631	0.672	0.709	0.741	0.771	0.798	0.823	0.846
5	0.577	0.625	0.668	0.709	0.745	0.776	0.805	0.832	0.851	0.879
6	0.603	0.652	0.695	0.733	0.767	0.798	0.827	0.854	0.878	0.900
7	0.622	0.672	0.715	0.753	0.788	0.819	0.848	0.874	0.898	0.900
8	0.634	0.686	0.730	0.768	0.803	0.836	0.864	0.889	0.900	0.900
9	0.644	0.696	0.741	0.780	0.815	0.847	0.875	0.900	0.900	0.900
10	0.653	0.705	0.749	0.788	0.822	0.854	0.883	0.900	0.900	0.900

Table 18 - Economical Loading Densities Δ_E . [21]

$\Delta_D \backslash P_m$	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600
2	0.41	0.44	0.48	0.52	0.55	0.58	0.62	0.65	0.68	0.71
3	0.46	0.51	0.55	0.58	0.62	0.65	0.68	0.71	0.74	0.76
4	0.50	0.54	0.59	0.63	0.66	0.70	0.73	0.75	0.78	0.80
5	0.52	0.57	0.61	0.65	0.69	0.72	0.75	0.78	0.80	0.82
6	0.54	0.59	0.63	0.67	0.70	0.73	0.76	0.79	0.81	0.84
7	0.55	0.60	0.64	0.68	0.72	0.75	0.78	0.80	0.83	0.86
8	0.56	0.61	0.66	0.70	0.73	0.76	0.79	0.82	0.84	0.87
9	0.58	0.63	0.68	0.72	0.75	0.79	0.81	0.84	0.86	0.88
10	0.60	0.65	0.70	0.74	0.77	0.80	0.83	0.86	0.88	0.90
Δ_1	0.160	0.1745	0.1885	0.2025	0.216	0.2285	0.241	0.253	0.265	0.276
Δ_H	0.492	0.532	0.568	0.600	0.631	0.660	0.687	0.711	0.736	0.762

Table 19 - Values of Parameter B_E for Economical Loading Conditions. [21]

$\Delta_D \backslash P_m$	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600
2	1.45	1.47	1.48	1.49	1.50	1.51	1.56	1.60	1.64	1.68
3	1.74	1.76	1.78	1.80	1.83	1.84	1.85	1.87	1.89	1.90
4	1.94	1.96	2.00	2.03	2.05	2.06	2.07	2.08	2.10	2.10
5	2.07	2.10	2.12	2.19	2.15	2.17	2.19	2.21	2.24	2.27
6	2.20	2.22	2.24	2.24	2.24	2.25	2.26	2.30	2.32	2.41
7	2.28	2.30	2.30	2.31	2.33	2.35	2.37	2.39	2.48	2.56
8	2.34	2.36	2.40	2.42	2.44	2.46	2.48	2.52	2.55	2.83
9	2.47	2.50	2.54	2.57	2.60	2.62	2.64	2.66	2.69	2.71
10	2.58	2.61	2.68	2.70	2.72	2.74	2.80	2.82	2.83	2.85

Table 20 - Characteristics η_K and η_D for
Economical Loading Conditions [21.7]

Λ_D	2	3	4	5	6	7	8	9	10
For all pressures $\eta_K = \frac{l_K}{l_D}$	0.82	0.75	0.70	0.66	0.63	0.60	0.57	0.59	0.63
$\eta_D = \frac{p_{av.}}{p_m}$ $\left\{ \begin{array}{l} \text{At } p_m = 1800 \\ \text{At } p_m = 3600 \end{array} \right.$	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.52	0.50
	0.79	0.73	0.66	0.60	0.55	0.50	0.45	0.42	0.40

2. FUNDAMENTAL RELATIONS AND DIAGRAM FOR BORE DESIGN DATA.

It has been shown in the investigation of the most advantageous and economical loading density that the optimum utilization of the volume of the bore and of the powder charge is obtained under the condition of complete burning of the powder in the bore ($l_K/l_D = 0.5-0.7$).

For this reason, the basic formula for deriving the fundamental relations interconnecting the design data for the bore and the loading conditions is the formula for the velocity of the projectile in the second period, in the instant of emergence of the projectile from the bore, where v_D is predetermined, and the volume and length of the bore and the length of the path of the projectile are to be found:

$$v_D^2 = v_{np}^2 \left\{ 1 - \left(\frac{\Lambda_K + 1 - \alpha \Delta}{\Lambda_D + 1 - \alpha \Delta} \right)^2 \left[1 - \frac{B\Theta}{2} (1 - z_0)^2 \right] \right\}, \quad (119)$$

where:

$$v_{np}^2 = \frac{2gf\omega}{\varphi\Theta q}; \quad \Lambda_K = \frac{l_K}{l_0}; \quad \Lambda_D = \frac{l_D}{l_0}; \quad \Lambda_D + 1 = \frac{l_D + l_0}{l_0} = \frac{W_{KH}}{W_0}$$

It will be desirable to represent equation (119) in the following form:

$$(\Lambda_D + 1 - \alpha\Delta)(1 - r')^{\frac{1}{\theta}} = (\Lambda_K + 1 - \alpha\Delta)(1 - r'_K)^{\frac{1}{\theta}},$$

where:

$$\frac{v_D^2}{v_{np}^2} = \varphi r'_D = r'; \quad \frac{v_K^2}{v_{np}^2} = \frac{B\theta}{2}(1 - z_0)^2 = r'_K;$$

Let us adopt the following designation:

$$(\Lambda_K + 1 - \alpha\Delta) \left[1 - \frac{B\theta}{2}(1 - z_0)^2 \right]^{\frac{1}{\theta}} = K.$$

By solving the basic equation with respect to $\Lambda_D + 1 = l_D/l_0 + 1 = W_{KH}/W_0$ and transferring W_0 to the right-hand side, we obtain:

$$W_{KH} = W_0 \left[\frac{K}{(1 - r')^{\frac{1}{\theta}}} + \alpha\Delta \right] \quad (120)$$

for the entire volume of the bore, and:

$$l_D = l_0 \left[\frac{K}{(1 - r')^{\frac{1}{\theta}}} + \alpha\Delta - 1 \right] \quad (121)$$

for the total length of the path of the projectile through the bore.

As is known from the tables of Professor Drozdov, at a predetermined value for p_m and at a chosen loading density Δ , the quantities Λ_K and B entering into the expression for K , and consequently also K itself, depend only upon p_m and Δ :

$$K = f(p_m, \Delta).$$

At predetermined values for Δ and v_D , the quantity r' is a function of ω/g only, since:

$$r' = \frac{\varphi q v_D^2 \theta}{2 g \omega f} = \frac{a + b \frac{\omega}{q} \theta}{\frac{\omega}{q} f} \frac{v_D^2}{2g}.$$

At a predetermined value for v_D , the product $\frac{\theta}{f} \frac{v_D^2}{2g} = \text{const.} = k_v$.

At the tabular values $f = 950,000$, $\theta = 0.2$, $g = 98.1 \text{ dm/sec}^2$:

$$k_v = \frac{\theta}{f} \frac{v_D^2}{2g} = \frac{v_D^2 \left(\frac{\text{dm}}{\text{sec}} \right)}{932 \cdot 10^6};$$

It is possible to compute this quantity in advance, and therefore r' is a function of ω/q only:

$$r' = k_v \frac{a + b \frac{\omega}{q}}{\frac{\omega}{q}} = f_2 \left(\frac{\omega}{q} \right).$$

The volume of the chamber is $W_0 = \omega/\Delta$.

Subsequently, for convenience in graphical representations, we shall introduce the relative quantities W_{KH}/q and W_0/q ; then:

$$\frac{W_0}{q} = \frac{1}{\Delta} \frac{\omega}{q} = f_3 \left(\frac{\omega}{q}, \Delta \right),$$

i.e., the chamber volume is a function of only two variables, namely Δ and ω/q .

In that case, the ratio of the entire volume of the bore W_{KH} to the weight of the projectile q , which is expressed by the formula:

$$\frac{W_{KH}}{q} = \frac{W_0}{q} \left[\frac{K(p_m \cdot \Delta)}{(1 - r')^{\frac{1}{\theta}}} + \alpha \Delta \right], \quad (122)$$

will, at predetermined d , q , v_D , and p_m , also be a function of only two variables, namely Δ and ω/q .

In place of the quantities W_{KH}/q and W_0/q , it is possible to introduce into equation (122) the relative lengths of the entire bore and chamber in calibers.

If the corrected length of the volume of the bore is designated as $l_0 + l_D = L'_{KH}$, where $sL'_{KH} = W_{KH}$, then:

$$\frac{L'_{KH}}{d} = \frac{l_0}{d} \left[\frac{K(p_m, \Delta)}{(1 - r')^{\frac{1}{\theta}}} + \alpha \Delta \right], \quad (123)$$

$$\frac{l_0}{d} = \frac{W_0}{sd} = \frac{W_0}{n_s d^3} = \frac{1}{n_s} \frac{W_0}{q} \frac{q}{d^3} = \frac{c_q}{n_s} \frac{1}{\Delta} \frac{\omega}{q} \text{ being a function of } \Delta \text{ and } \omega/q.$$

The actual length of the bore is $L_{KH} = l_{KM} + l_D = l_0/\chi + l_D$.

Upon designating $n' = 1 - 1/\chi = 1 - l_{KM}/l_0 = \delta_0/l_0$, we obtain:

$$L_{KH} = \frac{l_0}{\chi} + l_D = l_0 + l_D - \left(l_0 - \frac{l_0}{\chi} \right) = L'_{KH} - l_0 n'.$$

By substituting for L'_{KH} its expression in (123), we obtain:

$$\frac{L_{KH}}{d} = \frac{l_0}{d} \left[\frac{K(p_m, \Delta)}{(1 - r')^{\frac{1}{\theta}}} + \alpha \Delta - n' \right]; \quad (124)$$

and furthermore:

$$\frac{l_D}{d} = \frac{l_0}{d} \left[\frac{K(p_m, \Delta)}{(1 - r')^{\frac{1}{\theta}}} + \alpha \Delta - 1 \right]. \quad (125)$$

Intercomparison among all the formulas presented above leads to the conclusion that, at predetermined d , q , v_D , and p_m (which is in fact, what is usually predetermined in ballistic design), the design data for

the bore, i.e., the volume of the entire bore and of its working part, the chamber volume, the lengths corresponding to these volumes, and the actual length of the bore with proper allowance for the widening of the chamber, are functions of only the two variable loading conditions Δ and ω/q .

Consequently, each of the above-mentioned design quantities can be expressed in a three-dimensional coordinate system by a surface in the following coordinates:

$$Z, \Delta, \frac{\omega}{q},$$

where Z may be $\frac{W_{KH}}{q}$, $\frac{W_D}{q}$, $\frac{W_0}{q}$, $\frac{sL_{KH}}{q}$, or $\frac{L'_{KH}}{d}$, $\frac{l_D}{d}$, $\frac{l_0}{d}$, and $\frac{L_{KH}}{d}$.

Investigation shows that, at predetermined v_D and p_m , these surfaces (except for the surface representing chamber volumes) have the form of unsymmetrical "hammocks" with their convex sides turned downward. The lowest point of the "hammock" corresponds to the minimum of the quantity under consideration, and, for each of them - W_{KH} , W_D , and L_{KH} - there exists its own pair of values of Δ and ω/q at which these quantities have their minimum value (Fig. 159).

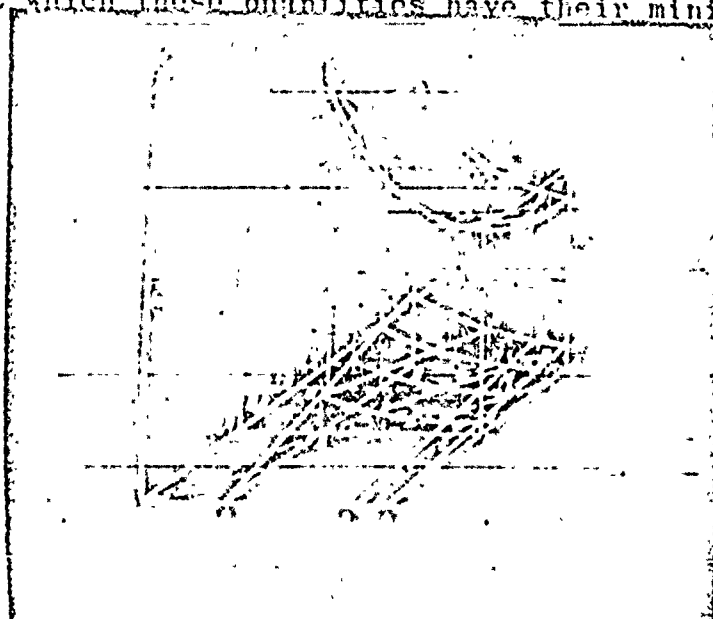


Fig. 159 - W_{KH} and W_0 as functions of ω/q and Δ ("Hammock" and "Slope").

This existence of a minimum for all the fundamental design elements of the bore, such as the volume of the entire bore W_{KH} , its total length L_{KH} , the path of the projectile through the bore l_D , or the working volume of the bore $W_D = sl_D$, has substantial significance in the development of a rational procedure for ballistic design.

The form of the surface $W_0/q = (1/\Delta)(\omega/q)$ will be determined with the greatest ease; upon being intersected by $\Delta = \text{const.}$ planes, it gives as functions of ω/q straight lines, which intersect the Δ axis; upon being intersected by $\omega/q = \text{const.}$ planes, it gives equilateral hyperbolas $W_0/q\Delta = \text{const.}$, which are located the higher the greater is ω/q .

Consequently, this surface has the form of an asymmetric hyperbolic slope passing through the Δ axis, the slope having a greater gradient at small Δ than at large Δ .

The form of the W_{KH} and W_0 surfaces is represented in Fig. 159, where Δ and ω/q are plotted along the coordinate axes, and W_{KH} and W_0 are plotted along the Z axis.

The loading density varies from Δ_1 , which corresponds to the given p_m as the charge burns instantaneously, to Δ_2 , which corresponds to the burning of the powder at the muzzle face.

The points A and B on the $\Delta - \omega/q$ plane correspond to loading density Δ_1 and the charges $\omega/q = 0.6$ and 1.2 ; the points D and C correspond to the loading density Δ_2 and the same charges.

The points a, b, c, d define the surface corresponding to the chamber volumes whose magnitudes are expressed by the ordinates Aa, Bb, Cc, and Dd. The lines bc and ad are equilateral hyperbolas; the lines ab and dc are straight lines passing through the Δ axis.

The ordinates Aa' , Bb' , Cc' , and Dd' express the magnitudes of the volumes of the bore of the gun at combinations of Δ and ω/q corresponding to the points A, B, C, and D. The figure makes it apparent that $Aa' > Bb' > Dd' > Cc' > Mm'$. The ordinate Mm' gives the minimum volume of the bore, and the point M on the $\Delta - \omega/q$ plane defines the values of Δ and ω/q at which this "gun with the minimum bore volume," or briefly "minimum-volume gun," is obtained.

The ordinate Mm defines the chamber volume of the gun with the minimum bore volume.

a) Case $W_0 = \text{const.}$

If an intersecting plane ZOAH is passed through the point A and the Z axis, its intersection with the chamber-volume surface will give the straight line ah, where $Aa = Hh$. On the W_{KH} surface, there corresponds to this straight line of equal chamber volumes the line $a'h'$ of decreasing bore volumes.

By proceeding along the line AH on the $\omega/q - \Delta$ plane, we maintain the tangent of its angle of slope $(\omega/q)(\Delta) = W_0/q$ constant; consequently, the straight lines OAH and OIK issuing from the origin of the coordinate system represent lines of equal chamber volume on the $\omega/q - \Delta$ plane; in this connection, the greater the angle of slope of the straight line the larger is the volume of the chamber ($Aa = Hh > Ii$).

The diagram shows that, if the design is subject to the condition that the chamber volume have a definite magnitude ($W_0 = \text{const.}$), this condition will be satisfied by different bore volumes (lines $a'h'$ and $i'k'$) and different ω/q and Δ , from among which it is possible to select those that are most suitable. In

this connection, ω/q varies in direct proportion to the loading density Δ .

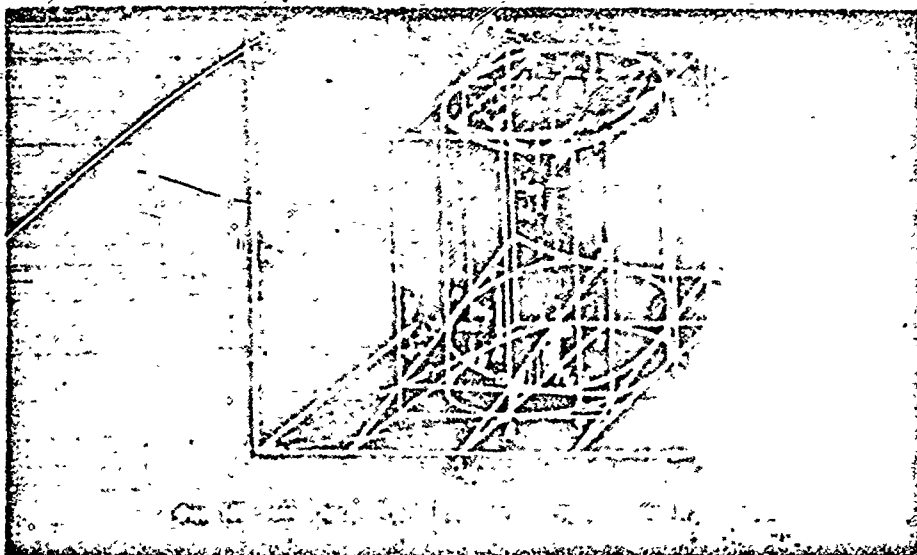


Fig. 160 - W_{KH} and W_0 as Functions of ω/q and Δ for $W_{KH} = \text{const.}$

b) Case $W_{KH} = \text{const.}$ (Fig. 160).

Upon intersecting the surface of the "hammock" by a plane parallel to the $\omega/q - \Delta$ plane, i.e., $W_{KH} = \text{const.}$, we obtain a line of intersection in the form of the oval a'h'b'g'. Consequently, the condition $W_{KH} = \text{const.}$ can be satisfied by various combinations of Δ and ω/q ; in this connection, except for the maximum and minimum values of ω/q and Δ , which define the extreme values of the boundaries of the oval (points a'b' and h'g'), two values for Δ correspond to every value of ω/q , and two values for ω/q correspond to every value of Δ . In conformity with this, the chamber volume also has two values - a greater and a smaller value - for every case.

The projection AHBG of the oval a'h'b'g' upon the $\omega/q - \Delta$ plane will also be an oval. On the hyperbolic-slope surface

expressing the chamber volumes, its intersection with the cylinder Aa'Hh'Bb'Gg' gives the line ahbg, which possesses a complex curvature in space. If tangents are drawn from the origin of the coordinate system to the projection of the oval on the $\omega/q - \Delta$ plane, the line OR will give the maximum value for the chamber volume R_r at the given W_{KH} , and the line OS will give the minimum value for the chamber volume S_s at the same bore volume W_{KH} .

Thus, equal bore volumes are represented on the $\omega/q - \Delta$ plane by concentric ovals, whose center is the point M_0 , which corresponds to the minimum bore volume at predetermined q , v_D , and p_m . The greater the bore volume the farther from the center M_0 does the corresponding oval lie.

3. DETERMINATION OF LOADING CONDITIONS Δ AND ω/q TO ATTAIN "MINIMUM-VOLUME GUN"

A. Determination of Loading Density Δ_{min}

to Attain Minimum Bore Volume (at Constant Value of ω/q or r').

In the general case, the expression for W_{KH}/q has the following form:

$$\frac{W_{KH}}{q} = \frac{\omega}{q} \frac{1}{\Delta} \left[\frac{(\Lambda_K + 1 - \alpha\Delta) \left[1 - \frac{B\theta}{2}(1 - z_0)^2 \right]^{\frac{1}{\theta}}}{(1 - r')^{\frac{1}{\theta}}} + \alpha\Delta \right] \quad (126)$$

The quantities Λ_K and B are not expressible analytically as functions of Δ , for which reason the partial differentiation of expression (126) to determine the minimum W_{KH}/q is not possible.

To investigate the form of the surface, it is necessary, after first assigning a constant value to ω/q , to vary Δ , i.e., to intersect our surface by planes parallel to the $Z-\Delta$ plane,

and to determine the form of the curves obtained in each section as a function of Δ . Thereupon, after successively assigning definite values to Δ , it is necessary to vary ω/q and also to determine the form of the curves obtained in each given section as a function of ω/q .

An analytical solution at $\omega/q = \text{const.}$ is obtained only for the simplest case $\psi_0 = 0$, with a powder possessing a constant burning area.

In this case (from the formula for the velocity in the second period):

$$\frac{W_{KH}}{q} = \frac{\omega}{q} \frac{1}{\Delta} \left[\frac{1 - \alpha \Delta}{\left(1 - \frac{B\theta}{2}\right)^{\frac{1}{\theta}}} \frac{1}{(1 - r')^{\frac{1}{\theta}}} + \alpha \Delta \right]; \quad (127)$$

Under the condition of constancy of the pressure p_m , the quantity B is connected with Δ by the following equation:

$$B = \frac{a_m \Delta}{1 - \alpha \Delta} = \frac{a_m}{\frac{1}{\Delta} - \alpha}, \quad (128)$$

where:

$$a_m = \frac{F_2(\theta) f}{p_m}$$

and, at $\theta = 0.2$, $F_2(\theta) = 0.320$.

By introducing $1/\Delta$ into the expression within the brackets, by replacing B by its expression (128), by introducing a new variable $y = 1/\Delta - \alpha$, and by designating $a_m \theta/2 = a''$, we obtain:

$$\frac{W_{KH}}{q} = \frac{\omega}{q} \left[\frac{y}{(1 - r')^{\frac{1}{\theta}} \left(1 - \frac{a''}{y}\right)^{\frac{1}{\theta}}} + \alpha \right] =$$

$$= \frac{\omega}{q} \frac{1}{(1-r')^{\frac{1}{\theta}}} \left[\frac{y}{\left(1 - \frac{a''}{y}\right)^{\frac{1}{\theta}}} + \alpha(1-r')^{\frac{1}{\theta}} \right]$$

Keeping in mind that r' is independent of Δ and y , differentiating the expressions within the brackets with respect to y , and equating the derivative to zero, we have:

$$1 - \frac{1}{\theta} \frac{a''}{y_H} \frac{1}{\left(1 - \frac{a''}{y_H}\right)} = 0,$$

from which:

$$y_H = \frac{1}{\Delta_H} - \alpha = \frac{1+\theta}{\theta} a'' = \frac{1+\theta}{2} a_m = \frac{1+\theta}{2} F_2(\theta) \frac{f}{p_m} \quad (129)$$

and:

$$\Delta_H = \frac{1}{\alpha + \frac{1+\theta}{2} F_2(\theta) \frac{f}{p_m}}$$

Let us designate:

$$\frac{1+\theta}{2} F_2(\theta) = \frac{1}{2} \left(\frac{2+\theta}{2+2\theta} \right)^{\frac{2+\theta}{\theta}} = F_3(\theta);$$

at $\theta = 0.2$, $F_3(\theta) = 0.192$, and:

$$\Delta_H = \frac{1}{\alpha + F_3(\theta) \frac{f}{p_m}} = \frac{1}{\alpha + 0.192 \frac{f}{p_m}}$$

The formula shows that, as p_m increases, an increase also

occurs in the loading density Δ_H at which the minimum bore volume is obtained. It does not depend upon the quantity ω/q ; consequently, at any desired value of $\omega/q = \text{const.}$, there exists a minimum bore volume, and it is always obtained at one and the same loading density Δ_H , which depends only upon the maximum gas pressure p_m .

We shall designate this loading density Δ_H as the most advantageous loading density.

The values of Δ_H applicable to our tables for the case $\psi_0 \neq 0$ were given approximately by Professor N.F. Drozdov [16] in 1940 and were then rendered more exact by the work of M.S. Gorokhov, [17] who gave a detailed table of values of Δ_H for various p_m in the range of 2000-4000 kg/cm² for $\chi = 1.06$ and 1.00.

Excerpts from this table are presented below:

p_m	2000	2400	2800	3200	3600	4000	
Δ_H	0.53	0.60	0.66	0.71	0.76	0.81	For $\chi = 1.06$

In the case of $\chi = 1.0$, Δ_H increases by approximately 0.02 in comparison with the values shown in the above tabulation.

For the numbers in the first table at $\chi = 1.06$, we have succeeded in deriving the following approximate empirical relation:

$$\Delta_H = \sqrt{\frac{p_m - 300}{5700}},$$

where p_m is given in kg/cm².

If expression (129) is substituted in the following formula for B:

$$B = \frac{a_m}{\frac{1}{\Delta} - \alpha}$$

we shall obtain:

$$B_H = \frac{2}{1 + \theta} = \text{const.}$$

Consequently, the minimum bore volume at any value of p_m and at the value of Δ_H corresponding thereto is always obtained at one and the same constant value of the parameter of loading B .

For the case of $\psi_0 = 0$, at $\theta = 0.2$, $B_H = 1.667$.

In accordance with the data of M.S. Gorokhov, for the tables of Professor Drozdov, at $p_0 = 300 \text{ kg/cm}^2$, B_H also has a constant value:

$$B_H \approx 1.91 - 1.93$$

B. Determination of Most Advantageous Weight of Charge to Attain Minimum Bore Volume (at $\Delta = \text{const.}$).

If, in equation (126), Δ is assigned different constant values, (i.e., if the $W_{KH}/q - \Delta - \omega/q$ surface is intersected by planes parallel to the $W_{KH}/q - \omega/q$ plane), it becomes possible to determine the conditions and values of ω/q at which, in these cases, the minimum bore volume is obtained. In this case, in equation (126), not only Δ will be constant, but, for a selected value of p_m , the following function:

$$K = (\sqrt{K} + 1 - \alpha\Delta) \left[1 - \frac{B\theta}{2}(1 - z_0)^2 \right]^{\frac{1}{\theta}} = f(p_m, \Delta).$$

will likewise be constant.

Let us introduce in the place of ω/q a new variable r' (cf. p. 808):

$$r' = k_v \frac{a + b \frac{\omega}{q}}{\frac{\omega}{q}},$$

where $k_v = v_D^2 \theta / 2gf$; from this:

$$\frac{\omega}{q} = \frac{ak_v}{r' - bk_v}.$$

Expression (126) will be transformed to the following form:

$$\frac{W_{KH}}{q} = \frac{1}{\Delta} \frac{ak_v}{(r' - bk_v)} \left[\frac{K}{(1 - r')^{\frac{1}{\theta}}} + a\Delta \right]. \quad (126')$$

By differentiating this expression with respect to r' , we obtain the condition for minimum W_{KH}/q in the following form:

$$\frac{1}{(1 - r')^{\frac{1}{\theta}}} - \frac{1}{\theta} \frac{r' - bk_v}{(1 - r')^{\frac{1}{\theta} + 1}} + \frac{a\Delta}{K} = 0$$

or:

$$\frac{1}{\theta} \frac{r' - bk_v}{(1 - r')^{\frac{1}{\theta} + 1}} - \frac{1}{(1 - r')^{\frac{1}{\theta}}} = \frac{a\Delta}{K} = f(p_m, \Delta). \quad (127)$$

At $\theta = \text{const.}$, the left-hand side of the above equation is a function of r' and of the predetermined velocity v_D , which enters into $k_v = v_D^2 \theta / 2gf$; the right-hand side $a\Delta/K$ is a function of p_m and Δ ; it is known in advance. By selecting values of r' , it is possible to satisfy equation (127) and to find the value r'_0 at which W_{KH}/q will have its minimum.

If the minimum bore length L_{KH} or the minimum total path of the projectile through the bore l_D are sought, then, by differentiating expressions (124) and (125), which have the same structure as expression (122), we shall obtain the following conditions

for the minima.

For the minimum bore length L_{KH} :

$$\frac{1}{\Theta} \frac{r' - bk_v}{(1 - r') \frac{1}{\Theta} + 1} = \frac{1}{(1 - r') \frac{1}{\Theta}} = \frac{\alpha\Delta - n'}{K}; \quad (128)$$

and for the minimum length of path:

$$\frac{1}{\Theta} \frac{r' - bk_v}{(1 - r') \frac{1}{\Theta} + 1} = \frac{1}{(1 - r') \frac{1}{\Theta}} = \frac{\alpha\Delta - 1}{K}. \quad (129)$$

Comparing all these three conditions, we see that their left-hand sides are the same, the differences residing only in their right-hand sides; the right-hand side of equation (127) has the greatest value, in (128) it is smaller, and in (129) it is negative (since $\alpha\Delta < 1$). In the first case, r'_0 will be greatest, in the last case least; as to the quantities $\omega/q = ak_v/(r'_0 - bk_v)$, they vary in the opposite direction. The significance of these relations will be clarified later.

For determining r'_0 to satisfy this equation, N.A. Krinitsky designed a nomogram which makes it possible to use the quantities $\alpha\Delta/K$ and $x' = 1 - bk_v$ to find r'_0 (Fig. 161).

The nomogram consists of two uniform scales - a left-hand scale of values of $x' = 1 - bk_v = 1 - b \frac{\Theta}{f} \frac{v_D^2}{2g}$ from 0.90 to 1.00 and a right-hand scale of values of $\alpha\Delta/K$ (or $\alpha\Delta - n'/K$ or $\alpha\Delta - 1/K$) - and a nonuniform curvilinear scale of values of r' in the middle.

Upon connecting with a straightedge the value of x' corresponding to the given velocity of the projectile and the value of

$\alpha\Delta K$ corresponding to the chosen values of Δ and p_m (found in the table of the function $\alpha\Delta K$ from the basic numbers for Δ and p_m , cf., p. 824), we read off at the point of intersection of the straight-edge with the r' scale the value r'_0 which satisfies the condition of minimum volume or length of the bore.

To determine the minimum bore volume, the value of $\alpha\Delta K$ is taken on the right-hand scale. To determine the minimum length of the bore in the presence of an expansion (widening) of the chamber,

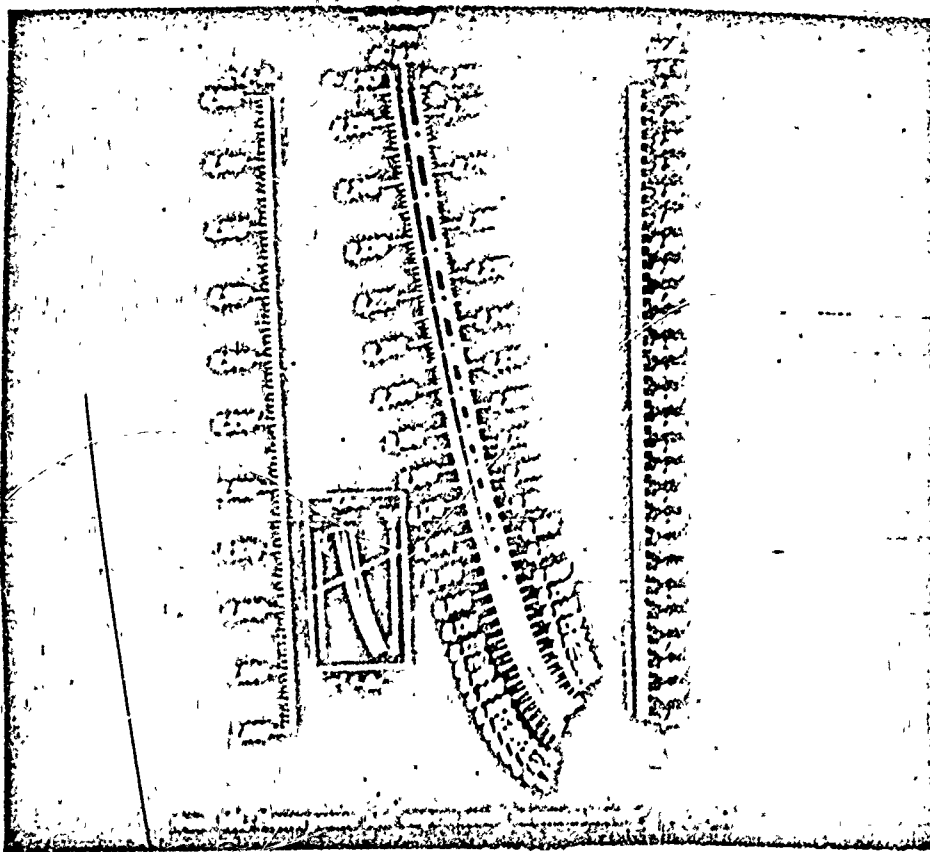


Fig. 161 - Nomogram for Determining Optimum r'_0 (Efficiency).

1) Values of r' at $\Theta = 0.181$; 2) key.

there is taken on the right-hand scale the quantity $(\alpha\Delta - n')K$, where $n' = 1 - (1/X)$. To determine the minimum length of the path of the projectile l_p , the quantity $(\alpha\Delta - 1/K) < 0$ is taken on the

right-hand scale.

The nomogram shows that, in conformity with these three cases of determining the minima at a predetermined v_D , the point on the right-hand scale moves downward, the value of r' decreases accordingly (the straight line rotates around a predetermined point x'), and consequently the values of ω/q and W_0/q increase, since $\omega/q = \frac{a}{r'} - b$ and $W_0/q = (\omega/q)(1/\Delta)$, where $\Delta = \text{const.}$

Thus, the gun with the minimum bore length L_{KH} , and to an even greater degree the gun with the minimum length of path l_D , are obtained with a larger chamber volume and a larger weight of the charge in comparison with the minimum-volume gun.

Therefore, the gun with the minimum bore volume which ensures the attainment of a predetermined initial velocity of the projectile v_D at a chosen pressure p_m has a smaller chamber volume and a smaller weight of the charge than the gun with the minimum bore length or with the minimum length of the path of the projectile, while having nearly the same actual bore length; for this reason, it may be designated as "optimum."

With the aid of the nomogram designed by Engineer Krinitsky, it is possible to follow the influence of other factors as well as upon the design data and the loading conditions.

For example, as the maximum pressure p_m for a predetermined value of v_D is increased, the quantity $\alpha\Delta/K$ increases, the point on the right-hand scale moves upward, and the quantity r' increases, but this reduces the weight of the charge and the chamber volume.

If Δ and p_m are maintained constant (the point $\alpha\Delta/K$ is fixed), then, as the velocity of the projectile changes (increases), x'

Table of α/κ (from JAU Tables) ($\alpha = 1$).

$P_n \backslash \Delta$	1600	1800	2000	2200	2400	2600	2800	3000	3200	3600	4000	4400	4800	5200	5600	6000	$P_n \backslash \Delta$
0.40	0.342	0.376	0.404	0.424	0.442	0.458	0.473	0.486	0.500	0.525	0.549	0.574	0.596	0.617	0.635	0.653	0.40
0.42	0.345	0.384	0.415	0.440	0.460	0.478	0.493	0.507	0.521	0.547	0.570	0.597	0.622	0.645	0.666	0.682	0.42
0.44	0.348	0.389	0.424	0.453	0.477	0.497	0.516	0.530	0.546	0.569	0.596	0.622	0.648	0.674	0.698	0.720	0.44
0.46	0.350	0.392	0.430	0.465	0.492	0.514	0.534	0.552	0.568	0.595	0.622	0.649	0.676	0.702	0.727	0.750	0.46
0.48	0.348	0.394	0.436	0.474	0.505	0.530	0.553	0.572	0.592	0.622	0.650	0.676	0.704	0.729	0.754	0.778	0.48
0.50	0.345	0.396	0.440	0.481	0.515	0.546	0.570	0.594	0.614	0.648	0.678	0.705	0.732	0.760	0.786	0.811	0.50
0.52	0.339	0.395	0.441	0.486	0.524	0.558	0.589	0.612	0.634	0.673	0.706	0.734	0.761	0.789	0.817	0.839	0.52
0.54	0.331	0.394	0.445	0.489	0.530	0.568	0.600	0.628	0.652	0.697	0.733	0.763	0.791	0.819	0.845	0.875	0.54
0.56	0.320	0.388	0.444	0.490	0.535	0.575	0.614	0.641	0.669	0.719	0.760	0.793	0.822	0.851	0.881	0.910	0.56
0.58	0.304	0.378	0.437	0.491	0.538	0.581	0.619	0.653	0.685	0.740	0.785	0.823	0.855	0.885	0.915	0.946	0.58
0.60	0.290	0.367	0.433	0.490	0.540	0.585	0.627	0.665	0.700	0.761	0.812	0.854	0.890	0.920	0.952	0.985	0.60
0.62	0.269	0.349	0.421	0.486	0.539	0.588	0.633	0.674	0.713	0.780	0.836	0.885	0.924	0.959	0.991	1.023	0.62
0.64	0.256	0.335	0.422	0.480	0.537	0.589	0.637	0.682	0.724	0.797	0.858	0.910	0.955	0.995	1.029	1.060	0.64
0.66	-	0.319	0.398	0.469	0.533	0.588	0.638	0.687	0.731	0.812	0.878	0.934	0.986	1.030	1.069	1.105	0.66
0.68	-	0.297	0.381	0.456	0.526	0.585	0.638	0.687	0.736	0.823	0.896	0.958	1.016	1.063	1.106	1.149	0.68
0.70	-	0.282	0.362	0.440	0.513	0.578	0.637	0.691	0.739	0.832	0.912	0.980	1.043	1.095	1.145	1.186	0.70
0.72	-	-	0.339	0.420	0.496	0.566	0.632	0.689	0.738	0.838	0.926	1.001	1.068	1.127	1.180	1.228	0.72
0.74	-	-	0.317	0.402	0.475	0.550	0.622	0.684	0.735	0.842	0.938	1.021	1.091	1.156	1.212	1.269	0.74
0.76	-	-	-	0.377	0.459	0.531	0.605	0.674	0.730	0.844	0.946	1.036	1.113	1.184	1.245	1.300	0.76
0.78	-	-	-	0.351	0.433	0.512	0.585	0.657	0.722	0.842	0.951	1.047	1.130	1.208	1.280	1.344	0.78
0.80	-	-	-	-	0.410	0.490	0.567	0.641	0.711	0.839	0.953	1.054	1.144	1.231	1.308	1.350	0.80
0.82	-	-	-	-	0.381	0.464	0.542	0.619	0.696	0.834	0.952	1.057	1.153	1.250	1.332	1.409	0.82
0.84	-	-	-	-	-	0.433	0.515	0.592	0.673	0.823	0.949	1.058	1.161	1.262	1.354	1.441	0.84
0.86	-	-	-	-	-	0.402	0.486	0.565	0.644	0.803	0.942	1.057	1.166	1.269	1.374	1.464	0.86
0.88	-	-	-	-	-	-	0.450	0.533	0.612	0.773	0.930	1.054	1.169	1.276	1.382	1.482	0.88
0.90	-	-	-	-	-	-	0.414	0.498	0.580	0.739	0.908	1.046	1.172	1.281	1.390	1.495	0.90
0.92	-	-	-	-	-	-	-	0.463	0.545	0.702	0.871	1.032	1.171	1.290	1.395	1.503	0.92
0.94	-	-	-	-	-	-	-	-	0.501	0.665	0.831	1.003	1.169	1.298	1.408	1.511	0.94
0.95	-	-	-	-	-	-	-	-	-	0.644	0.807	0.986	1.162	1.306	1.421	1.526	0.95

Table of Values of Function $a_2 = \frac{1}{(1 - r^1)^{\frac{1}{9}}}$; $\theta = 0.2$.

r^1 Hundredths	r^1 Thousandths									
	0	1	2	3	4	5	6	7	8	9
0.17	2.538	2.553	2.569	2.584	2.600	2.615	2.631	2.648	2.665	2.681
0.18	2.698	2.715	2.731	2.748	2.764	2.780	2.797	2.814	2.832	2.850
0.19	2.867	2.885	2.903	2.921	2.939	2.958	2.976	2.995	3.014	3.033
0.20	3.052	3.071	3.090	3.109	3.128	3.148	3.169	3.188	3.209	3.230
0.21	3.251	3.271	3.291	3.312	3.333	3.354	3.375	3.397	3.419	3.441
0.22	3.463	3.485	3.508	3.531	3.554	3.577	3.600	3.623	3.646	3.670
0.23	3.694	3.718	3.742	3.766	3.790	3.815	3.841	3.867	3.893	3.919
0.24	3.945	3.971	3.998	4.025	4.052	4.079	4.105	4.131	4.158	4.185
0.25	4.212	4.240	4.268	4.297	4.326	4.355	4.385	4.415	4.446	4.477
0.26	4.508	4.538	4.568	4.598	4.630	4.661	4.693	4.746	4.759	4.792
0.27	4.825	4.859	4.893	4.927	4.961	4.995	5.030	5.065	5.100	5.135
0.28	5.170	5.206	5.242	5.278	5.315	5.352	5.389	5.426	5.464	5.502
0.29	5.540	5.580	5.620	5.660	5.700	5.741	5.784	5.827	5.870	5.913
0.30	5.957	5.998	6.040	6.082	6.124	6.166	6.212	6.258	6.304	6.350
0.31	6.397	6.443	6.489	6.536	6.583	6.630	6.679	6.729	6.779	6.829
0.32	6.879	6.930	6.981	7.033	7.085	7.137	7.190	7.243	7.296	7.351
0.33	7.404	7.461	7.518	7.575	7.633	7.691	7.750	7.809	7.869	7.929
0.34	7.989	8.051	8.113	8.175	8.237	8.299	8.363	8.427	8.491	8.555
0.35	8.620	8.686	8.753	8.820	8.887	8.954	9.025	9.096	9.167	9.239

decreases, the point on the left-hand scale moves upward, the quantity r' increases and the quantities ω/q and W_0/q decrease, the volumetric expansion ratio Λ_D increases, and the gun is set up with a smaller relative chamber volume.

Knowing r'_0 , we determine the relative charge ω_0/q at which, in the presence of a given Δ , a bore of minimum volume is obtained, with the aid of the following formula:

$$\frac{\omega_0}{q} = \frac{ak_v}{r'_0 - bk_v} \cdot \frac{\frac{a}{r'_0} - b}{\frac{a}{k_v} - b}$$

Thus, the values of r'_0 and ω_0/q at which the minimum bore volume is obtained depend upon the quantity:

$$\Delta \left[\frac{\alpha\Delta}{K} - f(p_m, \Delta) \right]$$

and, for each value of Δ , r'_0 and ω_0/q will have their own values.

The values of $\alpha\Delta/K$ as a function of Δ and p_m are presented in a separate table, which shows that, as Δ increases at a given p_m , $\alpha\Delta/K$ at first increases until it reaches a maximum value, and then begins decreasing again. The maximum $\alpha\Delta/K$ defines that most advantageous loading density Δ_H at which the minimum bore volume is obtained.

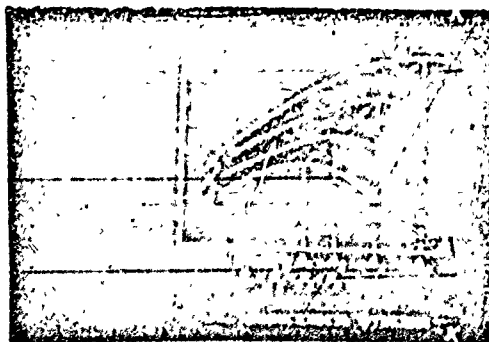


Fig. 162. - Relation between Function $\alpha\Delta/K$ and Loading Density.

Curves for $\alpha \Delta' K$ as functions of Δ at various p_m are presented in Fig. 162.

Thus, on the basis of investigations of the general relations of interior ballistics, there have been established other general relations connecting the design elements of the bore of the gun with the loading conditions at a predetermined caliber, weight of the projectile, its initial velocity, and maximum gas pressure, and there has been derived a procedure for determining the loading conditions at which a gun with the minimum bore volume, or the optimum gun, is obtained.

The diagrams presented for purposes of illustration show that a given velocity v_D at a chosen maximum pressure p_m can be obtained in the presence of the most diverse combinations of design data and loading conditions - with shorter or longer barrels, large or small chamber volumes, and large or small loading densities and charge weights.

CHAPTER 3 - APPLICATION OF DERIVED RELATIONS TO PRACTICAL DESIGN

1. DIRECTIVE DIAGRAM, ITS CONSTRUCTION AND INVESTIGATION.

To guide the expedient choice of variants in ballistic design, there is presented below a combined diagram of the design characteristics and some ballistic characteristics of a gun, which makes it possible to take into account some of the tactical and technical specifications imposed upon the gun as well. This diagram is designated as a "directive diagram," since it gives directives and instructions concerning the direction that must be followed in choosing variants satisfying the specifications imposed.

In constructing the diagram, use has been made of the diagrams of the variations of W_{KH}/q and W_0/q as functions of Δ and ω/q ("hammock" and "slope") presented above, which give the fundamental design characteristics of the gun. At predetermined q , v_D , and p_m , the directive diagram represents a projection upon the $\Delta - \omega/q$ plane of the sections of the W_{KH}/q and W_0/q surfaces formed by planes parallel to the $\Delta - \omega/q$ plane, which give in the section lines of equal W_{KH}/q and W_0/q . There is obtained, in a manner of speaking, a topographic map of the W_{KH}/q and W_0/q surfaces on the $\Delta - \omega/q$ plane (Fig. 163).

1. The fundamental point of the diagram, its "center," is the point M_0 with the coordinates Δ_H (most advantageous loading density) and ω_0/q (optimum relative charge), which represents the minimum-volume gun at predetermined q , v_D , and p_m , and which corresponds to the lowest point of the "hammock" $W_{KH}/q = f(\omega/q, \Delta)$.

2. There are circumscribed around the point M_0 oval-shaped

curves of equal bore volumes W'_{KH}/q , W''_{KH}/q , W'''_{KH}/q , known as the bore isochores, which are obtained as projections of intersections of the "hammock" by planes $W_{KH}/q = \text{const.}$ running parallel to the $\omega/q - \Delta$ plane.

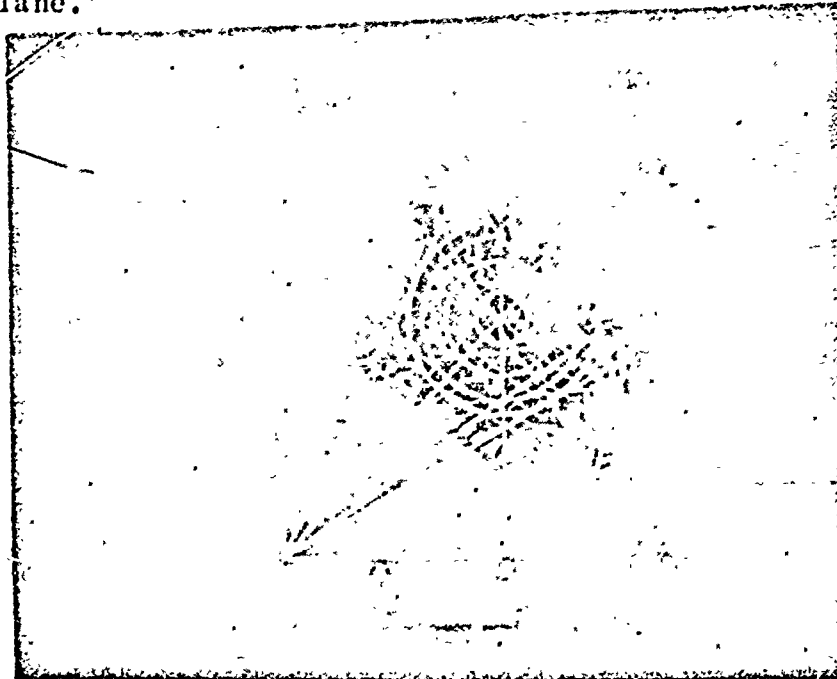


Fig. 163 - Directive Diagram for Choice of Variants.

The larger the bore volume the farther is the corresponding bore isochore from the point M_0 :

$$W_{KH_0} < W'_{KH} < W''_{KH} < W'''_{KH}.$$

The point M_0 may be imagined to lie in the center of a hollow, whose sides rise from the center M_0 toward the periphery.

3. The straight lines drawn from the origin of the coordinate system and continued until they intersect the ordinate at $\Delta = 1$, on which is written the scale of values of W_0/q , represent lines of equal chamber volumes W_0/q , since $W_0/q = (\omega/q)(1/\Delta) = \tan \alpha$. The larger the angle of slope α the larger is the chamber volume.

These lines represent projections of lines of intersection

of the surface of chamber volumes $W_0/q = f_1(\omega/q, \Delta)$ in the form of a hyperbolic slope by planes parallel to the $\omega/q - \Delta$ plane at various distances from the latter (cf. Fig. 159 above).

The straight line passing through the point M_0 represents the chamber volume for the minimum-volume gun W_{OH}/q .

The straight lines of equal W_0/q tangent at the left and right to the oval with a given bore volume W_{KH}/q give the maximum and minimum values for the chamber volume at the given bore volume. Definite pairs of values for ω/q and Δ correspond to them.

4. Knowing the values of W_{KH}/q and W_0/q for every point of the $\omega/q - \Delta$ plane, it is possible to determine the corresponding values for the volumetric expansion ratio Λ_D ($\Lambda_D = (W_{KH} - W_0)/W_0 = W_D/W_0$), the most important design characteristic of the bore of the gun. By plotting lines of equal Λ_D on the same diagram, we obtain a family of "iso- Λ_D " curves in the form of dotted lines with values of Λ_D marked on them (from 2.5 to 8.0). The greater Λ_D the farther to the right and the lower is the curve of equal Λ_D located.

5. In addition to these purely design characteristics, there has also been plotted on the diagram a family of curves of equal quantities $\gamma_K = l_K/l_D$, which characterize the position of the end of burning of the powder as a function of ω/q and Δ . On each of them is marked the corresponding value of γ_K from 0.3 to 1.0.*)

The line $\gamma_K = 1.0$ corresponds to the position of the projectile precisely at the muzzle face at the end of burning of the powder.

*) The data have been obtained by treatment of tables contained in the work by M.S. Gorokhov, "BALLISTICHESKI RASCHET ORUDIYA" "Ballistic Computation of Guns," 1941.

6. The loading parameter B at a given value of p_m is an increasing univalent monotonic function of Δ ; at $\Delta = \Delta_1 \dots$, $B = 0$; at $\Delta = \Delta_H$, $B_H = 1.91-1.93$.

The B - Δ curve is also contained in the diagram.

7. Since a very important factor in ballistic computations is the accuracy-life characteristic of a gun of design under given loading conditions, the formula of V.E. Slukhotsky for the characteristic of the number of shots N_{yc} was used to compute lines of equal values of N . These equal accuracy-life lines have also been plotted on the directive diagram; they are arranged in the form of straight lines nearly parallel to the Δ axis. The larger the quantities N_{yc} - the number of shots which the system is capable of withstanding - the lower is the corresponding straight line located: $N_3 > N_2 > N_1$.

Consequently, in order to improve the accuracy life, it is more advantageous from the point of view of the design to take, as far as possible, small ω/q , large Δ , and small chambers.

8. The heavy dashed-dotted line E-E in the diagram corresponds to the economical loading conditions; it passes from the upper left toward the lower right part of the diagram and intersects the $\Delta = \Delta_H$ ordinate somewhat below the point M_0 .

At pressures $p_m < 3200 \text{ kg/cm}^2$, the economical loading conditions (Δ_E and ω_E/q) give good results in ballistic design.

9. The characteristic $\eta_\omega = \frac{qv_D^2}{2g\omega} = \frac{v_D^2 \omega}{2gq}$ is reciprocal to the quantity ω/q plotted along the ordinate axis. As ω/q decreases at a predetermined value of v_0 , η_ω increases. The lines of equal η_ω are straight lines running parallel to the Δ axis. At a predetermined v_D , the η_ω scale can be plotted parallel to the ω/q

scale in the opposite direction.

10. An understanding of the variation of one of the fundamental ballistic characteristics, $\gamma_D = p_{av.}/p_m = \frac{\varphi q v_D^2}{2gW_D p_m}$, or better $\gamma'_D = \frac{q v_D^2}{2gW_D p_m}$ (without φ) can be obtained by proceeding along one of the straight lines of equal W_0/q .

At the points of its intersection with the oval of equal volumes W_{KH}/q , we have equal W_D/q and equal values of γ'_D . The point on this line located on the perpendicular line dropped from the point M_0 will be closest to the point M_0 and will correspond to the minimum bore volume W_{KH}/q ; at equal W_0/q , it will also correspond to the minimum working volume W_D/q and consequently to the maximum value of γ'_D .

It can be stated that, in the zone below and to the right of the line OM_0 , the closer the point under consideration to the point M_0 the smaller is W_{KH}/q , the larger W_0/q , and the larger the ratio of the muzzle energy to p_m and to the working volume of the bore.

2. APPLICATION OF DIRECTIVE DIAGRAM.

After clarifying the values and character of variations of all design characteristics of the bore of the gun, of the loading conditions, and of the conditions of the shot, it is possible to limit the zone of practical design on the directive diagram and to outline the general procedure for the selection of variants in order to obtain a solution with a minimum number of variants.

In the first place, there is eliminated from the region of

practical design the area to the right and upward from the $\gamma_K = 0.80$ line, since so large a magnitude of γ_K does not guarantee the actual combustion of the powder.

In the second place, there is eliminated the zone to the left and upward from the straight line OM_0 , since this is a zone of excessively large chamber volumes and small Δ_D .

There remains for practical design a zone in the form of a sector downward from the point M_0 , it being preferable, if conditions permit, to use the right-hand part of this sector at $\Delta > \Delta_H$. Such loading densities are in practice attainable at pressures of 2500-3200 kg/cm², to which correspond the most advantageous $\Delta_H = 0.62-0.71$. It is very difficult to attain $\Delta > 0.75$ with existing tubular powders, so that $\Delta = 0.75$ is as yet the limiting possible loading density. Grained powders with seven channels and fine powders for small arms make it possible to raise Δ to 0.80 and even to 0.90.

At very high pressures p_m (≥ 3500 kg/cm²), the most advantageous Δ_H increases to above 0.75, but it is in practice unattainable for powders possessing a tubular shape, and, in selecting variants, it becomes necessary to move to the portion of the sector on the left of Δ_H , to small loading densities for the given p_m , which leads to increased chamber volumes, reduced parameters B , and an earlier burning of the powder; γ_K may be smaller than 0.40. It is in this same zone that the solution for howitzerz should be sought, in order to obtain $\gamma_K \approx 0.25-0.30$ with a full charge; this will make it possible to obtain complete burning of the powder with reduced charges as well.

3. SEQUENCE OF COMPUTATIONS

A. Preliminary Choice of Basic Quantities.

On the basis of the relations established above among the design data for the bore of the gun, the loading conditions, and the energy characteristics of the shot, it is possible to outline the following sequence of ballistic computations.

1. From the predetermined magnitudes of the caliber d , the weight of the projectile q , and the initial velocity v_D , there are determined:

a) the coefficient of the weight of the projectile $c_q = q/d^3$ kg/dm³;

b) the coefficient of the power of the projectile $C_e = E_D/d^3 = \frac{q v_D^2}{2g d^3} = c_q \frac{v_D^2}{2g} \frac{\text{tn}}{\text{dm}^3}$.

2. From the quantity C_e , there is chosen in Table 21 the maximum gas pressure p_m , rounded off to the nearest 100 kg/cm² in the upward direction, as well as the coefficient of widening of the chamber λ .

Table 21 - Table for Selection of p_m and λ .

C_e	100	200	300	400	500	600	700	800	1000	1200	1400	1600
p_m	1840	2120	2300	2450	2600	2750	2875	3000	3200	3350	3500	3600
λ	1.04	1.09	1.14	1.20	1.26	1.33	1.40	1.49	1.70	1.97	2.35	2.91

The experience of the Great Patriotic War has shown the existence of a tendency toward increasing the pressure p_m at a given coefficient C_e .

For example, at $C_f = 1600$, $p_m = 3900-4000$. It is true that such high pressures cause difficulties with the extraction of shell cases and with obturation.

3. From the magnitude of the maximum pressure p_m , there is selected with the aid of the formula $\Delta_H = \sqrt{\frac{p_m - 300}{5700}}$ the most advantageous loading density Δ_H , at which, for the given charge ω/q and pressure p_m , the required velocity of the projectile v_D is obtained with the minimum volume of the bore of the gun.

B. Determination of Data for Minimum-Volume Gun.

4. For every pair of values of v_D and p_m , there exists at the loading density Δ_H an optimum value ω_0/q at which the bore volume has its minimum value (minimum minimorum).

The optimum weight of the charge ω_0/q is a function of p_m , v_D , Δ_H , and the coefficient b in the formula $\varphi = a + b(\omega/q)$. To find it in a preliminary way on the basis of the nomogram of N. A. Krinitsky from the basic quantities $\alpha\Delta/K = f(p_m, \Delta)$ (given in the table under the two headings p_m and Δ) and $x' = 1 - bk_v$, where:

$$k_v = \frac{\theta}{f} \frac{v_D^2}{2g} = \frac{v_D^2}{932 \cdot 10^6} \left[v_D - \frac{dm}{\text{sec}} \right],$$

there is found the complete coefficient of efficiency $r' = \varphi r_D$.

Thereupon, there is found:

$$\frac{\omega_0}{q} = \frac{a}{\frac{r'_0}{k_v} - b},$$

and then:

$$\frac{W_0}{q} = \frac{\omega_0}{q} \frac{1}{\Delta}; W_0 = \frac{W_0}{q} q \text{ and } l_0 = \frac{W_0}{s}.$$

After determining the auxiliary quantities:

$$K = \alpha \Delta : \frac{\alpha \Delta}{K} \text{ and } a_2 = \frac{1}{\frac{1}{\theta} (1 - r')}$$

(taken from the table in the preceding Chapter), there is found the value of:

$$\Lambda_D + 1 = K a_2 + \alpha \Delta$$

followed by:

$$W_D = W_0 \Lambda_D; l_D = l_0 \Lambda_D; W_{KH} = W_0 (\Lambda_D + 1).$$

From p_m and Δ , using the tables of Professor N.F. Drozdov or the GAU Tables, Issue No. IV, B_H and Λ_K are found; thereupon it is possible to determine:

$$\gamma_K = \frac{\Lambda_K}{\Lambda_D}; \frac{I_K}{d} = \sqrt{\frac{f}{g} \frac{c_q}{n_B}} \sqrt{B \varphi \frac{\omega}{q}} \text{ and } I_K = \frac{I_K}{d} d;$$

$$\left[\text{at } f = 950,000 \frac{\text{kg} \cdot \text{dm}}{\text{kg}}; g = 98.1; \sqrt{\frac{f}{g}} = 98.4 \right].$$

In this manner, there are found the data for the minimum-volume gun with the aid of analytical formulas and tables set up for the case of standard constants (constants of GAU Tables of 1943).

This gun is represented by the point U_0 on the directive diagram.

4a. If the special tables and nomogram for the determination of r'_0 do not happen to be accessible, but the GAU Tables, Part IV (TBR) are at hand, then, for computing the characteristics of the

minimum-volume gun, it is possible to make use of another method of approximation, since it is known that, as has been shown by computations, the quantity γ_{ω} for the optimum gun is a function of C_f , as defined by the following tabulation:

C_f	100-1000	1200	1400	1600
$\gamma_{\omega 0}$	85	84	83	82

After $\gamma_{\omega 0}$ is derived from the above, there is found:

$$\frac{\omega_0}{q} = \frac{v_D^2}{2g} \frac{1}{\gamma_{\omega 0}}.$$

Making use of the special form for ballistic computation, there is performed in the first column of the second page of the form a computation of the data for the gun having the minimum bore volume with predetermined d , q , v_D , and p_m . This is done with the aid of the 1943 GAU Tables, Part IV.

5. On the basis of the predetermined Δy , p_m , and $\gamma_{\omega 0}$, the following quantities are found in the sequence indicated in the form.

Ballistic Computation of Barrel

(Determination of Loading Conditions and of Fundamental Dimensions of Bore from GAU Tables)

Type of system being designed . . .

Supplementary conditions . . .

Caliber $d = \dots$ mm

Weight of projectile $q = \dots$ kg

Muzzle velocity $v_D = \dots$ m/sec

Cross-sectional area of bore $s = n_B d^2 = \dots$ dm²

Coefficient of weight of projectile $c_q = q/d^3 = \dots \text{ kg/dm}^3$

Muzzle energy $E_D = q \frac{v_D^2}{2g} = \dots \text{ tm}$

Coefficient of power $C_s = c_q \frac{v_D^2}{2g} = \dots \text{ tm/dm}^3$

Coefficient of chamber widening $\chi = \frac{l_0}{l_{KM}} = \dots$

Coefficient of allowance for secondary work $\varphi = a + b(\omega/q) \begin{cases} a = \dots \\ b = \dots \end{cases}$

$n_B \approx \begin{cases} 0.80-0.82 \text{ for artillery guns} \\ 0.82 \text{ for small arms; } \frac{v_D^2}{2g} = \dots \end{cases}$

$98.4c_q = \frac{v_D^2}{2g}$ ns Variants		Minimum Volume Gun	i	II	Variants		Minimum Volume Gun	I	II
	p_m				11	$\omega = \frac{\omega}{q} \cdot q$			
	Δ				12	$w_0 = \frac{\omega}{\Delta}$			
	η_ω				13	$l_0 = \frac{w_0}{s}$			
1	$\frac{\omega}{q} = \frac{v_D^2}{2g} \frac{1}{\eta_\omega}$				14	$l_D = l_0 \cdot \lambda_D$			
2	$b \frac{\omega}{q}$				15	$l_{KH} = \frac{l_0}{X}$			
3	a				16	$L_{KH} = l_{KH} + l_D$			
4	$\varphi = a + b \frac{\omega}{q}$				17	$\frac{L_{KH}}{d}$			
5	$n_v = \sqrt{\frac{\omega}{q\varphi}}$				18	$\frac{L_{CT}}{d}$			
6	$v_{mD} = \frac{v_D}{n_v}$				19	$\sqrt{B\varphi \frac{\omega}{q}}$			
7	B				20	$\frac{I_K}{d}$			
8	λ_K				21	I_K			
9	λ_D				22	$2e_1 = I_K \cdot 2u_1$			
					23	$7/10 \cdot 2e_1$			
10	$\eta_K = \frac{\lambda_K}{\lambda_D}$				24	$\frac{p_{av.}}{p_m} = \frac{\eta_\omega \varphi \Delta}{\lambda_D p_m}$			

Data for Construction of Pressure and Velocity Curves from GAU Tables

λ	$l_0 \lambda$	p	$v_{\text{tab.}}$	v	$t_{\text{tab.}}$	t

$$1) \frac{\omega_0}{q} = \frac{v_D^2}{2g} ; \gamma_{\omega_0} ; 2) b \frac{\omega}{q} ; 3) a = 1.03 ;$$

$$4) \varphi = a + b \frac{\omega}{q} ; 5) n_v = \sqrt{\frac{\omega}{\varphi q}} ; 6) v_{\text{tab. } D} = \frac{v_D}{n} .$$

Thereupon, with the aid of the GAU Tables, Part IV (or of the ANII Tables, for which $n_v = \sqrt{\frac{\omega}{q} \frac{1.05}{\varphi}}$), there are found:

$$7) B ; 8) \Lambda_K ; 9) \Lambda_D ;$$

and these data are used to determine:

$$10) \gamma_K = \frac{\Lambda_K}{\Lambda_D} ; 11) \omega = \frac{\omega}{q} q ; 12) w_0 = \frac{\omega}{\Delta} ; 13) l_0 = \frac{w_0}{s} ;$$

$$14) l_D = l_{0D} \Lambda_D ; 15) l_{KH} = \frac{l_0}{X} ; 16) L_{KH} = l_{KH} + l ; 17) \frac{L_{KH}}{d} ;$$

$$18) \frac{L_{CT}}{d} = \frac{L_{KH}}{d} + 1.5 - 2.0 ; 19) \sqrt{B \varphi \frac{\omega}{q}} ; 20) \frac{I_K}{d} = \frac{98.4}{n_B} c_q \sqrt{B \varphi \frac{\omega}{q}} ;$$

$$21) I_K = \frac{I_K}{d} d ; 22) 2e_1 = I_K \cdot 2u_1 ; 23) \gamma_D = \frac{p_{av.}}{p_n} = \frac{\gamma_{\omega \Delta}}{\Lambda_D \cdot p_n}$$

$$24) L'_{KH} = l_0 + l_D.$$

This computation is performed in the first column of the form, and its fundamental data are entered in the first row of the summary of results on the third page of the same form.

It is in this manner that there are determined the design data, loading conditions, and fundamental characteristics of a gun with the minimum bore volume at predetermined d , q , v_D , and p_m .

6. The minimum-volume gun is actually the optimum gun for velocities of the order of 1500 m/sec and higher, when, in consequence of the very large dimensions of the gun, the minimum volume and length of the bore constitute decisive and fundamental criteria in the choice of variants.

In this case, the solution is found at once, without supplementary variants, and is the only acceptable solution, even though the gun obtained has a relatively large volume chamber ($\Lambda_D = 3.0-3.5$), a relatively large charge weight ω/q , and a small coefficient of utilization of the charge γ_ω (82-85 tm/kg).

For projectile velocities lower than 1500 m/sec, of the order of 600-1200 m/sec, the minimum-volume gun is not to be recommended and represents merely a point of departure for other variants by setting a lower limit upon the bore volume.

C. Design at Usual Projectile Velocities.

To judge in what direction and how the loading conditions and design data of the bore must be changed in order to obtain a solution satisfying the requirements with a minimum number of variants, it is necessary to make use of the "directive diagram."

To obtain practically convenient solutions at $v_D = 600-1200$

m/sec, it is necessary to depart from the minimum-volume gun in the direction of reducing the weight of the charge and the chamber volume, the entire volume and length of the bore being somewhat increased, and the utilization of the unit weight of the charge γ_ω increasing at the same time.

If, in this connection, there is retained for the first variant the same loading density $\Delta = \Delta_H$, this corresponds on the directive diagram to a descent from the center of the diagram (the point M_0). For the purpose of reducing the number of variants while reducing ω/q , the following formulas can be recommended:

$$\frac{\omega}{q} = \frac{\omega_0}{q} \left(\frac{1}{4} + \frac{3}{4} \frac{v_D}{1500} \right) \text{ or } \frac{\omega}{q} \left(0.4 + 0.6 \frac{v_D}{1500} \right),$$

where v_D is stated in m/sec.

From this:

$$\frac{W'_0}{q} = \frac{\omega'}{q} \frac{1}{\Delta_H}.$$

If p_m and Δ_H are maintained constant, B and Λ_K likewise remain constant; and since Λ_D increases as ω/q decreases, $\gamma_K = \Lambda_K/\Lambda_D$ declines, and the characteristics of utilization of the bore volume of the gun p_{av}/p_m and R_D decline at the same time.

Let this value ω'/q be represented in the diagram (Fig. 163) by the point N , through which passes the isochore W''_{KH}/q .

For the chosen value $\omega'/q = \text{const.}$, the resulting gun has a minimum volume, since, as they move along the horizontal while ω/q is maintained constant, the points will move farther from M_0 , and the bore volume will increase.

Consequently, in this case, Δ_H is most advantageous not generally, but only as long as the weight of the charge is maintained constant, and this Δ_H is in this case advantageous only in a conditional manner.

For this reason, in order to improve the utilization of the bore volume and to transfer the end of burning to the muzzle face, which will also somewhat increase the muzzle pressure, the loading density should be increased if the gravimetric density of the powder permits this (in practice, if $\Delta_H \leq 0.70$).

Depending upon the tactical and technical specifications imposed, and in their absence on the basis of the requirement to give a rational ballistic solution, it is possible, in choosing further variants, to proceed from the point N in the following three directions (Fig. 163a).



Fig. 163a.

1. While maintaining the new chamber volume constant at W_0''/q , by moving from the point N to the right and upward along the line ON as far as the point n located on the perpendicular dropped from the point M_0 upon the straight line ON, and consequently by approaching the center M_0 , to obtain the minimum-volume gun at the given chamber volume.

Consequently, in this case, Δ_H is most advantageous not generally, but only as long as the weight of the charge is maintained constant, and this Δ_H is in this case advantageous only in a conditional manner.

For this reason, in order to improve the utilization of the bore volume and to transfer the end of burning to the muzzle face, which will also somewhat increase the muzzle pressure, the loading density should be increased if the gravimetric density of the powder permits this (in practice, if $\Delta_H \leq 0.70$).

Depending upon the tactical and technical specifications imposed, and in their absence on the basis of the requirement to give a rational ballistic solution, it is possible, in choosing further variants, to proceed from the point N in the following three directions (Fig. 163a).



Fig. 163a.

1. While maintaining the new chamber volume constant at W_0/q , by moving from the point N to the right and upward along the line ON as far as the point n located on the perpendicular dropped from the point U_0 upon the straight line ON, and consequently by approaching the center U_0 , to obtain the minimum-volume gun at the given chamber volume.

In this connection, it follows from the condition $W_0/q = (\omega'/q)$ ($1/\Delta$) = const. that the weights of the charges vary proportionately to the loading densities:

$$\omega_2 : \omega' = \Delta_2 : \Delta_H$$

To reduce the number of variants, it is permissible to take:

$$\Delta_2 = \Delta_H + 0.01 \Delta_D'$$

(Δ_D' corresponding to the charge ω'/q at $\Delta = \Delta_H$ in the point N).

In the point n, the maximum value is attained for $p_{av.}/p_m$ at the given volume chamber, η_K increases to 0.65-0.75, and Δ_D decreases slightly, since W_{KH} decreases at $W_0 = \text{const.}$

The resulting variant will undoubtedly be more rational than the variant corresponding to the point N, since, at the same chamber volume and at a smaller bore volume, it exhibits better energy characteristics η_D and η_K .

2. While maintaining the bore volume constant at W_{KH} , it is possible, by moving from the point N to the right along the line $W_{KH}''/q = \text{const.}$, by increasing Δ , and by increasing ω/q somewhat less, to obtain a gun with the given bore volume and with a minimum chamber volume (point n''), since, at the point n'', the angle of slope of the straight line On'' will be minimal (On'' is tangent to the curve $W_{KH}''/q = \text{const.}$). In this connection, $\Delta_{n''}$ will be somewhat greater than Δ_n .

In this case (in comparison with the point N), Δ_D will increase because of the diminution of the chamber volume, η_K and B will increase, and the value of η_D will increase somewhat (but less than in the first case).

3. While maintaining the weight of the charge constant at $\omega' q$, it is possible to proceed along the horizontal to the right from the point N, thus increasing Δ , moving away from the center M_0 , and thereby increasing W_{KH} and reducing the chamber volume, which increases Λ_D and raises the accuracy life.

In this connection, B and γ_K also increase.

At the maximum practically permissible loading density $\Delta = \Delta_n$ (point n'), there will be obtained a gun with the minimum chamber volume at the given weight of the charge.

For each of these three cases, the most advantageous loading density will exceed Δ_H , and, generally speaking, it will depend not only upon p_m , but also upon Λ_D . At the same time, the parameter B will also exceed $B_H \approx 1.91-1.95$.

All loading densities and all charge weights corresponding to the three cases discussed above will be located very close to the line E-E, which characterizes the combinations of Δ and $\omega' q$ capable of satisfying economical loading conditions.

For this reason, by choosing in the above-presented table of Δ_E for a predetermined p_m increasing magnitudes of Λ_D and the corresponding Δ_E , it is possible to obtain all three cases just discussed by a shorter route, without resorting to the preliminary transition to the point N at the same loading density Δ_H .

All these computations are performed in the subsequent columns of the same form for ballistic design, using the GAU Tables, Part IV (TBR), 1943, with a certain change in the order of operations.

D. Particular Design Cases.

I. Given d , q , v_D , and the chamber volume W_0' is assigned.

1. After computing C_e , Table 21 on p. 834 is used to choose p_m and X ; Δ_H is found, and one of the methods indicated above is used to compute the gun with the minimum bore volume (point M_0); there is obtained a definite value W_{OH} at the (optimum) charge ω_0/q (the first column of the form is filled in).

2. Since, at $\Delta = \text{const.} = \Delta_H$, the weight of the charge is proportional to the chamber volume, it is changed in such a manner as to obtain at once the predetermined chamber volume W'_0 :

$$\frac{\omega'}{q} = \frac{\omega_0}{q} \frac{W'_0}{W_{OH}};$$

whereupon the ballistic computation of the assigned variant is carried through to the end, and the second column of the form is filled in.

On the basis of the resulting values of Δ'_D and γ'_K , it is determined whether it is possible to stop at once at this variant, or whether it is necessary to proceed to Δ_E at the same W'_0 (to the point n).

In the latter case, with the aid of the formula $\Delta_2 = \Delta_H + 0.01 \Delta'_D$ or of Table 18, Δ_E is designated on the basis of p_m and Δ'_D (Δ_E and Δ_2 will be close to each other), and the computation of the second variant is performed at this Δ . There will be obtained a gun having a shorter length than in the first variant.

If this barrel length is for some reasons unsatisfactory, the pressure p_m should be changed, and the computation of all three variants should be repeated for the new pressure.

An increase in pressure will increase Δ_H and, with the same chamber volume W'_0 , will reduce Δ_D and shorten the barrel.

II. Given d , q , v_D , and the length of the bore in calibers

$L_{KH}/d = (l_{KH} + l_D)/d$ is assigned.

Preliminarily, on the basis of the coefficient $C_t = c_q \frac{v_D^2}{2g}$,

with the aid of Table 21, p_m and χ are determined, there is assigned for the minimum-volume gun:

$$\Delta_{DH} = 3.0 + 0.04 \frac{C_t - 100}{100}$$

(empirical formula), and the adjusted bore length $L'_{KH} = l_D + l_{KH}$, the total bore volume $W_{KH} = sL'_{KH}$, and W_{KH}/q are found for the assigned bore length L_{KH} :

$$L'_{KH} = L_{KH} \frac{\Delta_{DH} + 1}{\Delta_{DH} + \frac{1}{\chi}}$$

For the chosen value of p_m , there is found $\Delta_H = \sqrt{\frac{p_m - 300}{5700}}$,

whereupon the minimum-volume gun and its volume W_{KH} are computed.

If the resulting volume W_{KH} exceeds the assigned W'_{KH} , then it is impossible at the chosen pressure p_m to obtain a gun of the assigned volume and length, and it will be necessary to increase the pressure p_m (by 200-300 kg/cm²) and again compute for the new pressure its own minimum-volume gun.

In increasing the pressure for the computation of W_{KH} , it is possible to use as a guide the following approximate formula:

$$p_m \cdot W_{KH} \approx \text{const.}$$

If this new volume of the minimum-volume gun is smaller than the assigned volume, it is possible to proceed with the computation

of variants ensuring the attainment of a gun of the assigned length.

For this purpose, it is simplest of all to bracket the assigned bore length by choosing for the pressure p_m two values Λ_D' and Λ_D'' , and to take the two corresponding values Δ_E' and Δ_E'' from the table of Δ_E .

From the GAU Table IV (or from the ANII Tables), on the basis of the assigned Δ , p_m , and Λ_D , v_{TD}' and v_{TD}'' are found.

With the aid of the formulas:

$$\frac{\omega}{q} = \frac{a}{\frac{v_{TD}^2}{v_D^2} - b}$$

(for the GAU Tables, where $\varphi_{\text{tab.}} = 1$) and:

$$\frac{\omega}{q} = \frac{a}{1.05 \frac{v_{TD}^2}{v_D^2} - b}$$

(for the ANII Tables, where $\varphi_{\text{tab.}} = 1.05$), ω'/q and ω''/q are determined; there are found:

$$\frac{W_0'}{q} = \frac{\omega'}{q} \frac{1}{\Delta'} \text{ and } \frac{W_0''}{q} = \frac{\omega''}{q} \frac{1}{\Delta''},$$

followed by:

$$W_{KH}' = W_0'(\Lambda_D' + 1); W_{KH}'' = W_0''(\Lambda_D'' + 1);$$

$$(L_{KH}')' = \frac{W_{KH}'}{S}; (L_{KH}'')'' = \frac{W_{KH}''}{S};$$

and finally by:

$$(L_{KH})' = (L_{KH})' \frac{\Lambda_D' + \frac{1}{\lambda}}{\Lambda_D' + 1}; \quad (L_{KH})'' = (L_{KH})'' \frac{\Lambda_D'' + \frac{1}{\lambda}}{\Lambda_D'' + 1}.$$

Following this, the resulting values of L_{KH} are compared with the assigned length. If the latter is comprised between those found, the required values of Δ_E and Λ_D will be found by interpolation, and one more supplementary computation will be needed for verification.

If the assigned value of L_{KH} is either larger or smaller than the two values obtained, the required values of Δ_E and Λ_D will be found by extrapolation, and one supplementary variant will be needed for a check.

The variant obtained in either case ensures the assigned bore length at the minimum chamber volume.

If, together with the assignment of the bore length, there is imposed the supplementary requirement to obtain the smallest possible charge even if the chamber volume is somewhat increased, then, after establishing the bracket, both variants should be taken at $\Delta = \Delta_H$ and at different ω_1/q and ω_2/q (descending downward from the point H_0), and the results obtained should be used to apply corrections to ω/q for the final variant.

Example. To design an 85 mm antiaircraft gun having a bore length of about 60 calibers; $q = 9.2$ kg; $v_D = 900$ m/sec; $c_q = 15.0$; $C_i = 618$ tn/dm³; $\chi = 1.35$; $p_n = 2800$ kg/cm²; $\Delta_H = 0.66$. By the simplified method:

$$\gamma_H = 85 \text{ tn/kg} \cdot \frac{v_D^2}{2g} = 41.2 \cdot 10^4 \text{ cm}.$$

The computation is conducted with the aid of a 25 cm or 50 cm slide rule.

Two variants are computed in parallel: a minimum-volume gun at $\Delta_H = 0.66$, and a gun at the same Δ and with a charge diminished by means of the following formula:

$$\frac{\omega'}{q} = \frac{\omega_H}{q} \left(\frac{1}{4} + \frac{3}{4} \frac{v_D}{1500} \right) = \frac{\omega_H}{q} \left(\frac{1}{4} + \frac{3}{4} \frac{900}{1500} \right) = 0.70 \frac{\omega_H}{q}$$

For the first variant, there are taken for $C_\epsilon = 618$ by the simplified method:

$$\gamma_{\omega_H} = 85 \text{ tm/kg};$$

$$\gamma_{\omega} = 85;$$

$$\frac{\omega_H}{q} = \frac{v_D^2}{2g} \gamma_{\omega_H} = \frac{41.2}{85} = 0.485;$$

$$\varphi = 1.03 + \frac{1}{3} \frac{\omega}{q} = 1.03 + \frac{1}{3} 0.485 = 1.192;$$

$$n = \sqrt{\frac{\omega}{q} \frac{1}{\varphi}} = \sqrt{\frac{0.485}{1.192}} = 0.638;$$

$$v_{\text{tab.D}} = \frac{v_D}{n} = \frac{900}{0.638} = 1411;$$

$$\gamma_{\omega'} = 121;$$

$$\frac{\omega'}{q} = 0.70 \cdot 0.485 = 0.3395;$$

$$\varphi' = 1.03 + \frac{1}{3} 0.3395 = 1.143;$$

$$n' = 0.545;$$

$$v'_{\text{tab.D}} = \frac{900}{0.545} = 1652.$$

From the GAU Tables, Part IV, at $\Delta = 0.66$ and $p_m = 2800$,
there are found:

$$B_H = 1.926;$$

$$\Lambda_K = 2.498;$$

$$\Lambda_D = 3.104;$$

$$\eta_K = \frac{\Lambda_K}{\Lambda_D} = 0.805;$$

$$\omega = \frac{\omega}{q} q = 0.485 \cdot 9.2 = 4.46;$$

$$W_0 = \frac{\omega}{\Delta} = \frac{4.46}{0.66} = 6.76;$$

$$l_0 = \frac{W_0}{s} = \frac{6.76}{0.59} = 11.46 \text{ dm};$$

$$l_D = l_0 \Lambda_D = 11.46 \cdot 3.104 = 35.55;$$

$$l_{KH} = \frac{l_0}{\chi} = \frac{11.46}{1.35} = 8.49;$$

$$L_{KH} = l_{KH} + l_D = 44.04;$$

$$\frac{L_{KH}}{d} = \frac{44.04}{0.85} = 51.8;$$

$$\frac{L_{CT}}{d} = 51.8 + 1.7 = 53.5;$$

$$\frac{p_{av.}}{p_m} = \frac{\eta \omega \Delta}{\Lambda_D p_m} = 0.77;$$

$$p_D = 1440;$$

$$B_H = 1.926;$$

$$\Lambda_K = 2.498;$$

$$\Lambda_D = 5.49;$$

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of 60).

$p_{av.}/p_m = 0.595$ is considerably lower than in the first variant, and, in conformity with this, the muzzle pressure is $p_m = 760$ instead of 1440 in the first variant, i.e., is smaller by a factor of nearly two.

Now, while maintaining the chamber volume constant (proceeding along the line ON in Fig. 163), Δ and ω/q are proportionally increased, there being taken to reduce the number of variants:

$$\Delta_E = \Delta_H + \frac{\Lambda_D}{100} = 0.66 + \frac{5.5}{100} = 0.715 \text{ and } \frac{\omega_E}{\omega_H} = \frac{\Delta_E}{\Delta_H}.$$

Taking $\Delta_E = 0.71$ and $\Delta'_E = 0.72$, and performing the computation as in the first two variants, there are obtained:

N	Δ	$\frac{\omega}{q}$	B	Λ_D	η_K	w_0	l_D	L_{KH}	$\frac{L_{CT}}{d}$	$\frac{p_{av.}}{p_m}$	p_D	η_ω
3	0.71	0.365	2.216	5.37	0.625	4.732	43.05	49.0	59.4	0.615	860	113
3'	0.72	0.370	2.277	5.33	0.675	4.732	42.74	48.7	59.0	0.620	870	111.5

The data for the two variants nearly coincide; in comparison with the second variant, the length of the barrel has become shortened by 1.0-1.5 calibers, the muzzle pressure has increased by 100 kg/cm², the end of burning has shifted toward the muzzle face, and the value of η_K is good, being about 0.65.

Both these variants may be considered as being ballistically acceptable and as satisfying the imposed requirement to obtain a barrel length equivalent to about 60 calibers.

For the chosen variant (No. 3), the thickness of the powder is computed as follows:

$$\frac{I_K}{d} = \sqrt{\frac{f}{g} \frac{c_q}{n_s}} \sqrt{B \varphi \frac{\omega}{q}} = 98.4 \frac{c_q}{n_s} \sqrt{B \varphi \frac{\omega}{q}};$$

$$\frac{98.4 \cdot c_q}{n_s} = \frac{98.4 \cdot 15}{0.815} = 1810;$$

$$\sqrt{B \varphi \frac{\omega}{q}} = \sqrt{2.216 \cdot 1.152 \cdot 0.365} = 0.964;$$

$$\frac{I_K}{d} = 1810 \cdot 0.964 = 1745; I_K = 1745 \cdot 0.85 = 1483;$$

$$2e_{1\text{strip}} = 2u_1 \quad I_K = 2 \cdot 0.0575 \cdot 1483 = 0.0222 \text{ dm} = 2.22 \text{ mm}.$$

From the table correlating u_1 with the thickness of pyroxylin powder, a powder thickness of about 2 mm is associated with $u_1 = 0.0000073$.

Upon introducing the correction, there is obtained:

$$2e_{1\text{strip}} = 2.22 \frac{73}{75} = 2.16 \text{ mm; type } \frac{22}{1}$$

For a powder with seven channels:

$$2e_1 = 0.7 \cdot 2e_{1\text{strip}} = 0.7 \cdot 2.16 = 1.51 \text{ mm; type } \frac{15}{7}$$

Ballistic computation with the aid of the above procedure has required the computation of four variants.

Instead of first proceeding from the point W_0 downward to the point N while reducing ω/q and W_0 by 30% at the same Δ_H , and then ascending upward and to the right along the line ON while maintaining $W_0 = \text{const.}$ and increasing Δ and ω/q , it is possible, immediately following the computation of the data for the minimum-volume gun, to change over to the economic loading densities Δ_E , taking them from the table of Δ_E and selecting Δ_D for them.

In the table of Δ_E for a pressure $p_m = 2800$ at $\Delta_H = 0.66$, the value $\Delta_E = 0.72$ is associated with $\Lambda_D = 5.0$, while $\Delta = 0.73$ is associated with $\Lambda_D = 6.0$.

The course of the computation in this case differs somewhat from that presented above.

The following values are assigned:

$$p_m = 2800 \text{ and}$$

$$\Delta = 0.72, \Lambda_D = 5.0;$$

$$\Delta = 0.73, \Lambda_D = 6.0.$$

From the GAU Tables, Part IV (TBR), the following values are found:

Variants	Δ	Λ_D	B	Λ_K	η_K	$v_{\text{tab.D}}$
II'	0.72	5.0	2.277	3.596	0.719	1565
III'	0.73	6.0	2.341	3.86	0.643	1625

ω/q is found in accordance with the following formula:

$$\frac{\omega}{q} = \frac{a}{\left(\frac{v_{\text{tab.D}}}{v_D}\right)^2 - b} = \frac{1.03}{\left(\frac{v_{\text{tab.}}}{900}\right)^2 - \frac{1}{3}}.$$

The remaining data are found as in the first computation.

Variants	$\frac{\omega}{q}$	v_0	l_D	L_{KH}	$\frac{L_{CT}}{d}$	η_ω	$\frac{p_{av.}}{p_m}$	p_D	Λ_D
II'	0.3835	4.900	41.5	47.65	57.8	107.5	0.640	950	5.0
III'	0.352	4.435	45.1	50.66	61.3	117	0.584	795	6.0

In Variant II', the resulting barrel length is smaller than that required (57.8 d); in III', it is somewhat greater (61.3 d).

It is possible to interpolate these two variants to their mean and to obtain:

$$\begin{array}{llll} \Delta_E = 0.725; & \Delta_D = 5.5; & \gamma_K = 0.68; & B = 2.309; \\ \frac{\omega}{q} = 0.368; & W_0 = 4.67; & l_D = 43.3; & L_{KH} = 49.15; \\ \frac{L_{CT}}{d} = 59.5; & \gamma_\omega = 112.3; & \frac{p_{av.}}{p_m} = 0.612; & p_D = 870. \end{array}$$

The results of this computation coincide almost completely with the results of Computation No. 3', in which a different route was adopted, but almost the same point of the directive diagram was reached. The computation fully satisfies both the ballistic criteria $(\gamma_K, \gamma_D, \gamma_\omega)$ and the requirement for a definite barrel length. The type of powder is obviously the same as in the preceding case.

The entire computation has been performed in three variants.

All computations are performed and recorded in a form for the ballistic computation of the barrel, which contains a series of columns and headings for the operations and quantities.

For the finally selected variant, the GAU Tables (Parts I, II, and III) are used to solve the direct problem; i.e., the values of p , v , and t are found as functions of Λ or l , and these data are used to construct $p-l$, $v-l$, $p-t$, and $v-t$ curves for utilization in computing and designing the barrel, gun mount, tubes, and fuzes.

CHAPTER 4 - SUPPLEMENTARY INFORMATION

1. INFLUENCE OF VARIATION OF PRESSURE p_m UPON BORE DESIGN DATA AND LOADING CONDITIONS.

It is known that, in a given gun, in the presence of the same charge, the gas pressure p_m , the area under the curve $\int_0^{l_D} p dl$, and at the same time the velocity of the projectile increases as the thickness of the powder decreases, since:

$$v_D = \sqrt{\frac{2s}{\varphi m} \int_0^{l_D} p dl}.$$

Consequently, in inverting the problem, the same area $\int_0^{l_D} p dl$, which ensures the attainment of the predetermined velocity v_D , can be obtained with a shorter length of path of the projectile l_D by increasing the pressure p_m while maintaining the chamber volume and weight of the charge unchanged.

Consequently, an increase in pressure with a given chamber volume and a given weight of the charge must reduce the length of path of the projectile l_D and the length of the entire bore L_{KH} .

Together with an increase in the pressure p_m , the following loading densiti grow correspondingly:

Δ_1 for the instantaneous burning of the charge;

Δ_H - the most advantageous loading density;

Δ_E the economical loading density;

Δ_1 for the burning of the powder at the muzzle face.

The diagram expressing the dependence of W_{KH} and W_0 upon Δ at $\omega = \text{const}$, at a predetermined v_D , and at $p_m'' > p_m'$ will have the form

represented in fig. 164

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Fig. 164. Dependence of W_{KH} and W_0 Upon Δ at Various p_m .

1) An increase in the pressure p_m while Δ , ω , and W_0 are maintained constant (loading density Δ_H' , transition from the point c' to the point b') reduces the length of the bore to a lesser degree than if Δ_H were increased simultaneously in conformity with the increase in pressure (transition from the point c' to the point b'').

This is explained by the fact that the increased Δ_H'' is the most advantageous for the new pressure p_m'' , ensuring a bore of minimum length; on the other hand, the previous Δ_H' is no longer the most advantageous for the new pressure, and the length of the bore is greater.

2) As the pressure increases, apart from the total decrease in the length of the bore, the quantity Λ_D also decreases, i.e., the relative chamber volume increases.

3) The characteristic $\eta_K = l_K/l_D$ decreases considerably at $\Delta = \text{const}$ as p_m is varied; but, as Δ increases in conformity with the increased pressure p_m'' , η_K undergoes almost no change.

4) The product $p_m \cdot W_{KH,H}$ is close to being a constant.

Consequently, it may be considered that, as p_m increases in the presence of the same weight of the charge ω , the volume and length of the bore are inversely proportional to the pressure p_m .

This formula can be utilized for exploratory computations in ballistic design:

$$W_{KH}'' = W_{KH}' \frac{p_m'}{p_m''} \quad \text{or} \quad L_{KH}'' \approx L_{KH}' \frac{p_m'}{p_m''}$$

In this connection:

$$l_0'' = l_0' \frac{\Delta'}{\Delta''}$$

If, in computing the minimum-volume gun, its length is obtained greater than the predetermined length, an increase in pressure constitutes the only means available to satisfy the imposed condition.

2. EFFECT OF DIFFERENT POWDERS ON THE LOADING CONDITIONS AND GUN DESIGN DATA BASED ON BALLISTICS.

Besides pyroxylin powders, use is also made of more powerful nitroglycerol powders, which contain 20-40% of nitroglycerol. By having a higher burning temperature, these powders considerably shorten the accuracy life of the barrel. The search for means to increase the accuracy life of guns has also led to the use of so-called "cold" powders, which have a lower burning temperature and a smaller propellant force; these include, for example, nitroguanidine powders.

Since our tables are set up for definite powder characteristics, which correspond to pyroxylin powders, there arises the question of how a variation in the nature of the powder will be reflected in the

design data of the gun and in the loading conditions at given values of d , q , v_D , and p_m , a situation encountered in ballistic design.

The nature of a powder is characterized by the following factors: f - the propellant force of the powder; α - the covolume of the powder gases; u_1 - the rate of burning of the powder at $p = 1 \text{ kg/cm}^2$; the adiabatic index $k = 1 + \theta$, which depends upon the composition of the gases and upon their temperature in the bore.

It is known from courses in interior ballistics and from the study of powders that, for pyroxylin powders, $f = 85-95 \text{ tm/kg}$, $\alpha =$ about $1 \text{ dm}^3/\text{kg}$, and $\theta = 0.20$; for nitroglycerol powders, f and u_1 increase, and the covolume α and the index θ decrease, as the nitroglycerol content increases; in nitroguanidine powders, on the contrary, f and u_1 decrease, and the quantities α and θ increase.

In this connection, although the rate of burning u_1 changes with variations in the nature of the powder, it enters into the fundamental equations and relations not as a separate entity, but as a component of the pressure impulse I_K , which depends both upon u_1 and upon the thickness of the powder $2e_1$ ($I_K = \frac{e_1}{u_1}$). For this reason, in the subsequent discussion, the quantity u_1 will not be considered separately, but the impulse will be included among the characteristics of the loading conditions which are determined in ballistic computations.

Since, in ballistic design, the variant which serves as the point of departure is the minimum-volume gun (the center of the directive diagram), it is convenient in investigating the influence of variations in the nature of the powder to compare the design data and loading conditions for minimum-volume guns at predetermined v_D and p_m .

There are presented below some of the results of such investigations conducted by M.E. Serebryakov [22] and N.A. Krinitskii.

The computations were conducted for the following characteristics, which correspond to powders of different natures.

No.	Powder	$f \frac{tm}{kg}$	$\alpha \frac{dm^3}{kg}$	e	$\frac{f}{f_2} \%$
1	Nitroguanidine	86.5	1.10	0.220	91
2	Pyroxylin	95	1.00	0.200	100
3	Medium-power nitroglycerol	105	0.905	0.181	110.5
4	High-power nitroglycerol	115	0.825	0.165	121

Subsequently, each powder will be designated by its number; the data for pyroxylin are accepted as the reference unit = 100%.

The data for minimum-volume guns were determined by the general procedure involving the use of the nomogram of Krinitskii for the simplified case ($\psi_0 = 0$, $\kappa = 1$, $\alpha = 1/\delta$).

In the summary table below, the fundamental ballistic characteristics of minimum-volume guns are given as percentages for powders of various natures.

Table 22

Characteristics	Powder No.	1	2	3	4
	No.	Percentage			
Propellant force of powder f	1	91	100	110.5	121
Burning temperature T_1	2	83	100	122	146
Loading parameter B_H	3	98.3	100	101.6	103
Most advantageous loading density Δ_H	4	97	100	102.2	103.7
Optimum efficiency r'_0	5	111.2	100	89.2	80.6
Optimum relative charge ω_0/q	6	110.7	100	90.1	81.3
Chamber volume W_0	7	114.1	100	88.2	78.4
Volumetric expansion ratio Λ_D	8	91.8	100	108.3	117.4
Length of path of projectile l_D	9	104.7	100	95.2	92.0
Bore volume W_{KH}	10	107	100	93.3	88.6
Path at end of burning l_K	11	99.5	100	101.5	101
Pressure impulse l_K	12	100.6	100	99.6	98.9
$\gamma_K = \Lambda_K/\Lambda_D = l_K/l_D$	13	94.8	100	105.8	109.8
Muzzle pressure p_D	14	93.4	100	107.4	112.4
Coefficient of utilization of unit charge weight γ_ω	15	90.8	100	110.7	122.7
Coefficient φ	16	102	100	98.1	96.4
Gas temperature at emergence of projectile T_D	17	79	100	126	155
Average pressure $\eta_D = p_{av.}/p_m$	18	97.5	100	102.9	104.7
Accuracy life N_{ycn}	19	209	100	37.8	12.6
$1/f$	20	110	100	90.5	82.5

Investigation of the data presented in the table shows the following facts.

1) The optimum loading density and the parameter B_H increase slightly as the propellant force of the powder increases (lines 3 and 4).

2) The optimum efficiency r'_0 and the optimum charge ω_0/q vary

inversely proportionally to the propellant force of the powder (lines 5 and 6).

3) The coefficient of utilization of the unit weight of the charge γ_w varies directly proportionally to the propellant force of the powder (line 15).

4) The volumetric expansion ratio Λ_D varies almost proportionally to the propellant force of the powder (in somewhat lesser degree) (line 8).

5) The chamber volume varies in the opposite direction to the propellant force of the powder, but in somewhat greater degree (line 7).

6) The length of path of the projectile l_D also varies in the opposite direction to the propellant force of the powder, but in lesser degree (line 9).

7) The total volume of the bore varies in the opposite direction and in somewhat greater degree than l_D , but in lesser degree than the propellant force of the powder (line 10).

8) The path of the projectile at the end of burning l_K and the full pressure impulse I_K are practically independent of the nature of the powder (lines 11 and 12), but the thickness of powders with a greater propellant force will grow in conformity with the increase in u_1 , since $e_1 = I_K \cdot u_1$.

9) The characteristic of the end of burning of the powder $\gamma_K = l_K / l_D$ varies inversely proportionally to the variation in l_D , since l_K is approximately constant (line 13).

10) The muzzle pressure increases somewhat more slowly than the propellant force of the powder (line 14).

11) The muzzle gas temperature increases very sharply with an increase in the propellant force of the powder (line 17).

12) The average pressure increases very slowly with increasing propellant force of the powder (being nearly proportional to the loading density Δ_H) (line 18).—

13) The characteristic of the accuracy life of the bore varies extremely sharply (line 19); the change from pyroxylin powder to No. 4 nitroglycerol powder is accompanied by an eightfold drop in N_{ycn} , in spite of the more advantageous design data and loading conditions; the change to nitroguanidine powders is accompanied by a greater than twofold rise in N_{ycn} .

All these conclusions present a perfectly clear picture of the variation in the fundamental design data, energy characteristics, and loading conditions for the minimum-volume gun accompanying a variation in the nature of the powder.

As has already been shown in the theoretical fundamentals of ballistic design, the minimum-volume gun can be recommended for practical realization only at very high projectile velocities (1500 m/sec).

At lower projectile velocities, a departure from the minimum-volume gun in the direction of a smaller charge and chamber volume (on the directive diagram, downward and to the right from the point M_0) is indicated.

There arises the question whether such a departure will not alter the relations established in Table 22, and whether the relative character of the resulting relations will be maintained for such guns possessing other than a minimum volume.

The investigation presented in the same chapter shows that the relations indicated in Table 22 are maintained with small changes even if the minimum-volume gun is not used as the starting variant.

Thus, if the nature of the powder differs from that assumed in the GAU Tables, it is possible, once a gun has been designed in accordance with these tables, to introduce changes into the results of the computation by making use of the data in Table 22 in the present chapter, whereupon the results may be checked by the use of analytical formulas, of the method of Professor Drozdov, or of the method of the average l_{ψ} .

3. RELATION BETWEEN WEIGHT OF BARREL AND ITS DESIGN ELEMENTS AT PREDETERMINED PROJECTILE VELOCITY AND AT GIVEN MAXIMUM PRESSURE p_m .

In some cases, the weight of the barrel may be one of the criteria in the selection of one or another variant.

For this reason, along with the knowledge of the variation in the design elements and loading conditions at predetermined v_D and p_m , it is also desirable to know the variation in the weight of the barrel Q_{CT} .

One and the same v_D at the same p_m can be obtained both from a short barrel with a relatively large chamber (minimum-volume gun) at

Λ_D = about 3 and from a long barrel with a small chamber (Λ_D = about 10). In this connection, the muzzle pressure, which determines the barrel-wall thickness at the muzzle face, will in the first case equal about one-half the maximum pressure (p_D/p_m = about 0.5), while in the second case p_D/p_m = about 0.15-0.20 (fig. 165).

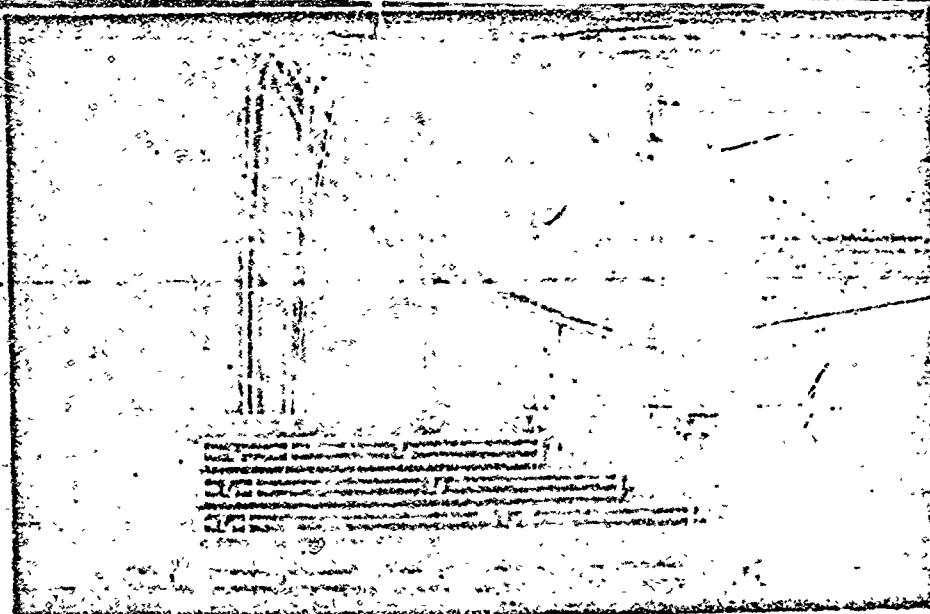


Fig. 165 - Pressure Curves in Guns with Various Λ_D at Predetermined v_D and p_m .

In the first case, we have a long cylindrical part and a short conical part with thick walls at the muzzle face; in the second case we have a considerably shorter cylindrical part with a long cone and a thin wall at the muzzle face.

It is necessary to clarify in an exploratory manner how the weight of the barrel will vary with variations in the characteristic Λ_D .

A longitudinal section through the barrel is represented schematically in fig. 166.

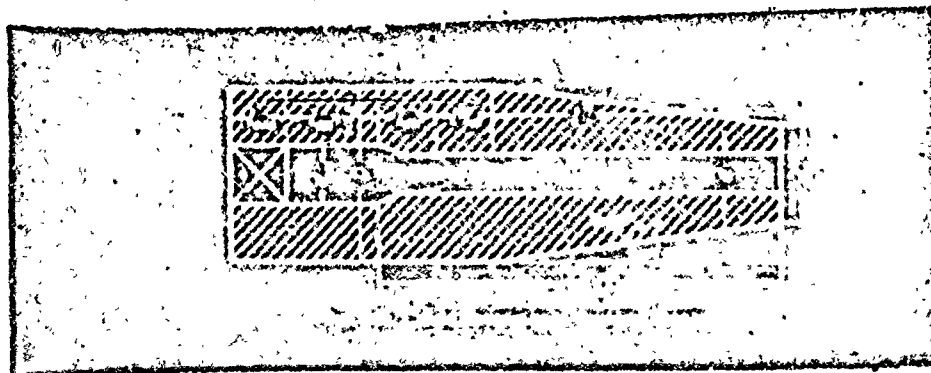


Fig. 166 - Scheme of Longitudinal Section of Barrel.

The gun has the following characteristics:

Outer diameter of cylindrical breech D .

Outer diameter of muzzle end of barrel d_2 .

Caliber of gun d .

Average chamber diameter d_{KM} .

Length of breech ring l_{KA3} .

Chamber length $l_{KM} = l_0/\chi$.

Path of projectile at instant of maximum pressure l_m .

Reserve in cylindrical part for possible shift of maximum pressure toward muzzle face $l' = \text{about } 0.6 l_0 \approx l_m$.

Length of conical part of barrel l'' .

$$l'' = l_D - (l_m + l') \approx l_D - 1.2 l_0.$$

If the density of steel is designated as δ' ($\delta' = 7.85 \text{ kg/dm}^3$), the weight of the barrel will be expressed by the following formula:

$$Q_{CT} = \delta' \left\{ \frac{\pi}{4} D^2 (l_{KA3} + l_{KM} + l_m + l') + \frac{1}{3} \frac{\pi}{4} (D^2 + D d_2 + d_2^2) l'' - \frac{\pi}{4} d^2 (l_0 + l_D) \right\},$$

where the first term in parentheses is the volume of the solid cylindrical part of diameter D , the second is the volume of the truncated cone of diameters D and d_2 and length l'' , and the third is the volume of the entire bore.

We separate from the above expression the weight of the breech ring $Q_{KA3} = (\pi/4) D^2 l_{KA3} \delta'$, and, by designating $A = D/d$ and $a_2 = d_2/d$, taking l_0 out of the parentheses, and dividing both sides of the equation by d^3 in order to represent the weight of the

barrel in relative units, we obtain:

$$\frac{Q_{CT}}{d^3} = \frac{Q_{KA3}}{d^3} + \delta' \frac{\pi}{4} \frac{l_0}{d} \left\{ \left(\frac{1}{X} + 1 \right) A^2 + \frac{1}{3} (A^2 + Aa_2 + a_2^2) (\Lambda_D - 1) - (1 + \Lambda_D) \right\}.$$

After dividing this by $c_q = q/d^3$, we have:

$$\frac{Q_{CT}}{q} = \frac{Q_{KA3}}{q} + \delta' \frac{W_0}{q} \left\{ \left(\frac{1}{X} + 1 \right) A^2 + \frac{1}{3} \left[1 + \frac{a_2}{A} + \left(\frac{a_2}{A} \right)^2 \right] A^2 (\Lambda_D - 1) - (1 + \Lambda_D) \right\}. \quad (127)$$

The quantity $A = \frac{D}{d}$ is a function of the maximum pressure p_m ; the quantity $a_2 = \frac{d_2}{d}$ is a function of the muzzle pressure p_D , which is itself a function of p_m and Λ_D ; the values of p_D/p_m , a_2/A , and A are tabulated below as functions of p_m and Λ_D .

Table of Values for $A = \frac{D}{d} = f(p_m)$

p_m	1800	2200	2600	3000	3600
A	1.68	2.00	2.56	3.79	5.10

Table of Values for $\frac{p_D}{p_m} = f(p_m, \Lambda_D)$
Under Economical Loading Conditions

$\Lambda_D \backslash p_m$	3	4	6	8	10
1800	0.543	0.451	0.323	0.244	0.208
2200	0.545	0.445	0.305	0.237	0.198
2600	0.521	0.430	0.396	0.220	0.185
3000	0.500	0.405	0.271	0.207	0.172
3600	0.465	0.373	0.250	0.189	0.154

Table of Values for $\frac{a_2}{A} = \frac{d_2}{D} = f(p_m, \Lambda_D)$

$\Lambda_D \backslash p_m$	3	4	6	8	10
1800	0.744	0.738	0.696	0.667	0.660
2200	0.690	0.650	0.600	0.570	0.560
2600	0.563	0.539	0.477	0.465	0.442
3000	0.396	0.368	0.328	0.312	0.301
3600	0.314	0.285	0.249	0.236	0.228

The dependences of A and a_2 upon the pressure have been taken from Table 2 in the "Handbook on Design of Gun Barrels and Breech-blocks" by E.K. Larman, the mechanical-strength safety factor used being 1.33, and the elastic limit being assumed to be $\sigma_e = 6000 \text{ kg/cm}^2$.

Consequently:

$$\frac{p_1}{\sigma_e} = \frac{1.33}{6000} p = \frac{p}{4500} \text{ kg/cm}^2.$$

Since the length of the breech ring $l_{KA3} \approx 1.5d$, it follows that:

$$Q_{KA3} = \frac{\pi}{4} D^2 \cdot 1.5d \delta';$$

$$\frac{Q_{KA3}}{d^3} = 7.85 \frac{\pi A^2}{4} 1.5 \approx 10A^2.$$

In Formula (127), the relative weight of the barrel is expressed in terms of the ballistic characteristics of the bore W_0/q , Λ_D , and X , and of the quantities A and a_2/A , which also depend upon the ballistic characteristics p_m , Λ_D , and p_D . The formula is useful for exploratory computations.

Computations performed with the aid of this formula have shown that, at predetermined v_D and p_m , the weight of the barrel as a function of Λ_D varies along a curve possessing a minimum at $\Lambda_D \approx 5-6$ (Fig. 167).

Consequently, if there has been imposed the requirement to obtain a minimum-weight barrel, it is necessary to take $\Lambda_D \approx 5.6$.

GRAPHIC NOT REPRODUCIBLE

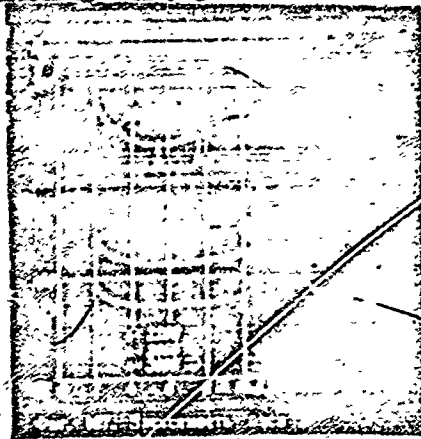


Fig. 167 - Weight of Barrel as a Function of Λ_D at Predetermined v_D and p_m .

4. APPLICATION OF VARIOUS BALLISTIC TABLES.

Ballistic computations may be carried out with the aid of any desired available tables, including the tables of Professor Drozdov for strip-type powder ($\kappa = 1.06$) with "normal" constants, the 1933 ANII Tables with the same constants, the 1943 GAU Tables with somewhat modified constants ($\alpha = 1$, $\varphi = 1$), the 1933 tables of the Chair of Interior Ballistics for powders with a constant burning area ($\kappa = 1$, $\lambda = 0$) and for any desired values of f and φ , and the tables of M.S. Gorokhov [17] for $\kappa = 1.06$ and for $\kappa = 1.00$ with the remaining constants "normal."

Maximum convenience for ballistic computations attaches to the GAU Tables, Part IV (TBR), and to the tables of M.S. Gorokhov.

Prior to the start of the computation, it is necessary to select for any table a coefficient of agreement between the computations and experiments, for which purpose it is, in turn, necessary to process the results of firing tests from artillery systems already accepted

for armament and approaching in type the system being designed.

Computations for ten of our systems firing with small relative charges ($\omega/q < 0.20$) have shown [21] that good agreement with experimental v_D and p_m in computations with the aid of the ANII Tables is obtained at $\varphi = 1.05$, whereas, when a correction is applied to make $\varphi = 1.03 + \frac{1}{3} \frac{\omega}{q} > 1.05$ at a predetermined pressure p_m , the initial velocities obtained fall short of the experimental velocities by approximately 3%.

Consequently, in spite of the fact that the ANII Tables are compiled for strip-type powder ($\kappa = 1.06$), whereas the systems accepted for armament fire either with tubular powders ($\kappa = 1$) or with powders possessing seven perforations ($\kappa \approx 0.7$), both of which burn more progressively than strip-type powder, nevertheless the adoption at $\omega/q < 0.20$ of the value 1.05 for φ - a value smaller than the actual value - compensates somewhat for the more degressive character of burning of strip-type powders and gives computed results for v_D that are very close to the results of firing tests conducted with tubular or strip-type powders.

Note: If, in conducting computations with the aid of the ANII Tables at the same $\omega/q < 0.20$, φ is taken in accordance with the theoretical formula $\varphi = a + \frac{1}{3} \frac{\omega}{q}$, where $a = 1.03-1.06$ depending upon the type of gun (according to Slukhotskii), but v_D is determined by

means of the formula $v_D = v_{\text{tab}} \sqrt{\frac{\omega}{q} \frac{1.05}{\varphi}}$, then, if the computed

values for v_D coincide with the experimental values, the pressure p_m determined from the tables is obtained 10% higher than the experimental p_m .

The application of a correction to φ should be adopted at high values of $\omega/q > 0.20$, when $\varphi = 1.05$ will differ too much from $\varphi = 1 + \frac{1}{3} \frac{\omega}{q}$. Nevertheless, the above-mentioned lack of consistency in the character of burning of powders, which requires some compensation by the reduction of φ , will manifest itself at large ω/q as well, and this will make it necessary to reduce the coefficient $b = 1/3$. For example, some designers take the formula $\varphi = 1.05(1 + \frac{1}{4} \frac{\omega}{q})$, which, at large ω/q , gives a smaller value than $\varphi = 1.03 + \frac{1}{3} \frac{\omega}{q}$.

As for the quantity φ , it exerts a rather considerable effect upon the computed design data of the bore (as φ decreases, the length of path and the length of the bore also decrease).

Comparison among the tables of Professor Drozdov, the tables of Gorokhov, the ANII Tables, and the GAU Tables indicates that, at predetermined Δ and p_m , different values are obtained for B and Λ_K , as follows:

B	$< B$	$< B$	$< B$
Drozdov	ANII	Gorokhov	GAU
Λ_K	$< \Lambda_K$	$< \Lambda_K$	$< \Lambda_K$
Drozdov	Gorokhov	GAU	ANII

and this, at a predetermined v_D and at identical φ or b , leads to different values for the length of path l_D and the length of the bore L_{KH} , the difference increasing with increasing v_D ; the smallest values for l_D and L_{KH} are obtained in working with the tables of Professor Drozdov, and the largest with the ANII tables, the difference being small (about 2%) for $v_D = 1000$ m/sec and as large as 7-8% for $v_D = 1500$ m/sec.

At identical Δ and B , the GAU Tables give higher values for p_m than the tables of Professor Drozdov, the difference increasing with the increase in Δ . Thus, for $\Delta = 0.50$, at identical B , $p_{mGAU} - p_{mDr} =$ about 2%; for $\Delta = 0.60$ the difference is 2.5-3.0%; for $\Delta = 0.70$ it is 4-5%; and for $\Delta = 0.80$ it is 5-6%. Such a discrepancy cannot be explained by the fact that the covolume in the GAU Tables is $\alpha = 1$ instead of 0.98 as in the tables of Professor Drozdov.

In the ANII tables the pressures p_m approach the values given by Drozdov; in Gorokhov's tables these values are 1-2% smaller than the p_m values given in the GAU tables.

From the tables of Gorokhov compiled for different κ (1.06 and 1.00), it is possible to draw the conclusion that, as κ varies from 1.06 to 1.00 at predetermined Δ and B , the pressure p_m decreases by 4-6%, the change in p_m being the greater the larger B and Δ .

In any case, tables compiled even on the basis of a mathematically exact method, for constants of definite values, cannot in all cases give complete agreement with experimental data, since the theoretical solution does not take into account all details of the phenomenon of the shot, and every mathematically exact method based on definite assumptions is merely an approximation with respect to the actual phenomenon, which is much more complex than the scheme adopted in the assumptions.

It is for this reason that, for every method of solution and for every table, it is necessary to select its own coefficient of agreement, which will give the best coincidence with experiment. In using one of the tables enumerated above for a ballistic computation, it is necessary, on the basis of experimental data for

"related" guns under firing conditions close to those provided for by the design, to determine the coefficient of agreement of the given table with experiment and to utilize this coefficient in the design.

In the case of pyroxylin powders, agreement with experiment is attained best of all by the selection of the coefficient b in the formula $\varphi = a + b \frac{3}{q}$.

It has already been indicated above that, at identical φ and b , for predetermined p_d and $v_D = 1500$ m/sec, the ANII Tables give a length of path of the projectile l_D that is 7-8% greater than that obtained with the fundamental tables of Professor Drozdov.

Identical values of l_D can be obtained with the aid of either set of tables by selecting different values for the coefficient φ or b .

For example, if, on the basis of the tables of Professor Drozdov, the values obtained for b are $1/3$ in one case and $1/5$ in another, the corresponding values for b obtained from the ANII Tables will be $1/4$ and $1/6$, respectively.

This circumstance confirms the necessity of selecting the coefficient b for the purpose of ensuring agreement between each type of tables and experiment; it also indicates the errors in the procedure of compiling the ANII Tables at high velocities.

There is presented below a procedure for determining φ and b on the basis of firing tests with the aid of various tables.

5. DETERMINATION OF COEFFICIENT b FROM TABLES

The quantity a in the coefficient $\varphi = a + b \frac{\omega}{q}$ is usually assumed to be 1.03 for high-power guns, 1.04-1.05 for guns of moderate power, 1.05-1.06 for howitzers, and 1.10 for small arms; the quantity b is subject to determination on the basis of the results of firing tests.

For a given gun, let there be known^(*):

$$W_0, s, l_D, q, \omega, p_m \text{ and } v_{D \text{ op}};$$

In addition, there are determined:

$$\Delta = \frac{\omega}{W_0}, l_0 = \frac{W_0}{s} \text{ and } \Lambda_D = \frac{l_D}{l_0}.$$

The table for the given Δ having been selected, B is found from Δ and from p_m , and, in the table of velocities, at the same Δ , B and Λ_D are used to determine $v_{\text{tab. } D}$ and $v_{D \text{ calc.}} = v_{\text{tab. } D} \sqrt{\frac{\omega}{q}}$. Since $v_{D \text{ op}} = v_{\text{tab. } D} \sqrt{\frac{\omega}{\varphi_{\text{op}} q}}$ (from the GAU Tables) and $v_{D \text{ op}} = v_{\text{tab. } D} \sqrt{\frac{\omega}{q} \frac{1.05}{\varphi}}$ (from the ANII Tables), it follows that, in working with the

GAU Tables ($\varphi = 1$):

ANII Tables ($\varphi = 1.05$):

$$\varphi_{\text{op}} = \left(\frac{v_{D \text{ calc.}}}{v_{D \text{ op}}} \right)^2;$$

$$\varphi_{\text{op}} = 1.05 \left(\frac{v_{D \text{ calc.}}}{v_{D \text{ op}}} \right)^2;$$

$$b_{\text{op}} = \frac{\varphi_{\text{op}} - a}{\frac{\omega}{q}};$$

$$b_{\text{op}} = \frac{\varphi_{\text{op}} - a}{\frac{\omega}{q}}.$$

(*) The subscript op of the last value stands for "determined." translator.

Drozdoz and the tables of the Chair of Interior Ballistics, it is necessary, first of all, on the basis of the quantities Δ and p_m , to determine B (or C), and then to determine

$$\Lambda_K = \frac{l_K}{l_0} \text{ and } \eta_K = \frac{\Lambda_K}{\Lambda_D}$$

If $\eta_K < 1$ (the burning of the powder is complete), v_D^2 calc. is computed as follows from the tables of Professor Drozdov ($\varphi = 1.05$);

$$v_{D \text{ calc.}}^2 = \frac{2g}{1.05} \frac{f}{\theta} \frac{\omega}{q} \left\{ 1 - \frac{(\Lambda_K + 1 - \alpha\Delta)^\theta}{(\Lambda_D + 1 - \alpha\Delta)^\theta} \left[1 - \frac{B\theta}{2}(1 - z_0)^2 \right] \right\} = 29,790^2.$$

$$\frac{\omega}{q} \left\{ 1 - \frac{K^\theta}{(\Lambda_D + 1 - \alpha\Delta)^\theta} \right\}; \varphi_{op} = 1.05 \left(\frac{v_{D \text{ calc.}}}{v_{D \text{ op}}} \right)^2; b_{op} = \frac{\varphi - \alpha}{\frac{\omega}{q}}.$$

According to the tables compiled by the Department of Interior Ballistics ($\varphi = 1$), for any f and $\theta = 0.2$:

$$v_{D \text{ calc.}}^2 = \frac{2gf}{\theta} \frac{\omega}{q} \left[1 - \frac{BD}{(\Lambda_D + 1 - \alpha\Delta)^\theta} \right],$$

where B and D are found from the table on the basis of the same values for p_m , Δ , and C.

$$\varphi_{op} = \frac{v_{D \text{ calc.}}^2}{v_{D \text{ op}}^2}; b_{op} = \frac{\varphi - \alpha}{\omega/q}.$$

The tables of M.S. Gorokhov are in part constructed in the same manner as the tables of Professor Drozdov, in that the quantities B and Λ_K are given directly as functions of Δ and p_m (Appendix III). In addition, there exist special tables for determining the most

advantageous solutions at various p_m in the case of maximum φ_D (Δ_H , r' , $\frac{W_{KH}}{\omega}$, $\Lambda_D + 1$, etc.).

If $\gamma_K > 1$ (the burning of the powder is incomplete), it is impossible to employ the formula for v_D^2 calc. and to compute it with the aid of the tables of Professor Drozdov and of the Department of Interior Ballistics, and it becomes necessary to use only the ANII or GAU Tables in conjunction with the formulas presented above.

6. INFLUENCE OF VARIATION OF φ AND b UPON RESULTS OF COMPUTATIONS OF DESIGN DATA (Λ_D , l_D).

From the fundamental equation, we have:

$$\begin{aligned} \Lambda_D + 1 - \alpha\Delta &= \frac{(\Lambda_K + 1 - \alpha\Delta) \left[1 - \frac{B\theta}{2} (1 - z_0)^2 \right]^{1/\theta}}{(1 - r')^{1/\theta}} = \frac{K}{(1 - r')^{1/\theta}} \\ &= \frac{K}{(1 - \varphi r_D)^{1/\theta}} \end{aligned} \quad (128)$$

At predetermined Δ and p_m , the quantity $K = \text{const}$; at a given φ , $r_D = \text{const}$. We differentiate equation (128) with respect to φ , whereupon we multiply and divide the right-hand side by φ :

$$d\Lambda_D = \frac{K}{\theta} \frac{r'}{(1 - r')^{\frac{1}{\theta} + 1}} \frac{d\varphi}{\varphi} \quad (129)$$

Upon dividing (129) by (128), we obtain:

$$\frac{d\Lambda_D}{\Lambda_D + 1 - \alpha\Delta} = \frac{1}{\theta} \frac{r'}{(1 - r') \varphi} \frac{d\varphi}{\varphi} \quad (130)$$

where, as r' varies in the range of 0.200-0.333 and $\theta = 0.2$, the

quantity $\frac{1}{\theta} \frac{r'}{1-r'}$ (the coefficient of $\frac{d\varphi}{\varphi}$) varies in the range of 1.25-2.50.

It is seen from formula (130) that Λ_D increases and decreases with φ , this relative variation of Λ_D being greater than the relative variation of φ .

From the formula presented above:

$$b = \frac{\varphi - a}{\frac{v_D}{v_{D_{op}}}};$$

it follows that:

$$db = \frac{d\varphi}{\frac{v_D}{v_{D_{op}}}} \text{ and } \frac{db}{b} = \frac{d\varphi}{\varphi - a}. \quad (131)$$

Since the difference $\varphi - a$ is usually small, the relative variation of b is considerably greater than the variation of φ , and the quantity $\varphi = \left(\frac{v_{D \text{ calc.}}}{v_{D_{op}}} \right)^2$. Consequently, the divergence in the velocities $v_{D \text{ calc.}}$ obtained by computation with the aid of various tables necessitates a change in b_{op} required to give the same values of v_D .

It follows from Formula (131) that:

$$\frac{d\varphi}{\varphi} = \frac{\varphi - a}{\varphi} \frac{db}{b} \quad (132)$$

Upon substituting (132) into (130), we obtain a direct connection

between the variation of Λ_D and the variation of b :

$$\frac{d\Lambda_D}{\Lambda_D + 1 - \alpha\Delta} = \frac{1}{\theta} \frac{r'}{1 - r'} \frac{\varphi - a}{b} \frac{db}{\varphi} = \frac{1}{\theta} \frac{r'}{1 - r'} \frac{\omega}{q} \frac{db}{\varphi}$$

Upon substituting $r' = \frac{\varphi k_v}{\frac{\omega}{q}}$, where $k_v = \frac{\theta}{f} \frac{v_D^2}{2g}$, we obtain:

$$\frac{d\Lambda_D}{\Lambda_D + 1 - \alpha\Delta} = \frac{k_v}{\theta} \frac{db}{1 - r'} = \frac{v_D^2}{2gf(1 - r')} \frac{db}{1 - r'}$$

Consequently, the influence of the difference in the quantity b increases with an increase in the initial velocity of the projectile v_D , confirming the results obtained in performing computations with the aid of the ANII Tables and the tables of Professor Drozdov.

The relations presented above confirm the necessity of exact selection of the value for the coefficient b_{op} on the basis of the results of firing tests from an existing "related" gun which is close in its data to the gun being designed. This is especially important in the case of high initial velocities.

Only in such a case is it possible to expect that the results of the design will agree well with practice.